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CONTROL OF SEWER OVERFLOWS BY POLYMER INJECTION

by

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Grant No. 11020 DZU

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment for public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communications link between the researcher and the user community.

One source of water pollutants is un-controlled overflows from sanitary and combined sewers. This report deals with one possible method for the reduction or elimination of such overflows.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

ABSTRACT

In the past, the operator of a sewage collection system has had three alternatives for dealing with overloaded sanitary sewers; ignoring them, diverting them to storm sewers and streams, or pumping to other locations. An EPA-sponsored research program entitled, "Polymers for Sewer Flow Control," Contract No. 14-12-34, suggested a possible alternative system wherein the capacity of a sewer might be increased by the injection of certain water-soluble chemicals to reduce turbulent friction. This concept was further developed and demonstrated during this project, EPA Grant entitled, "Elimination or Reduction of Sanitary Sewer Overflows in the Bachman Creek Sewershed," which was executed in Dallas, Texas. This report was prepared to help operators of sanitary sewage collection systems determine the feasibility of using turbulent friction reduction, designing an injection facility, choosing a friction reducing material, and evaluating the results.

This report was submitted in fulfillment of Grant No. 11020 DZU by the Water Utilities Department of the City of Dallas under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from May 1969 to December 1973.

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The work of N. C. Glaze, E. O. Buch, and the Special Projects field crews was essential to the successful operation of the injection facility.

The design of working components of the station, and the production of graphs, figures, and the text were ably supported by the engineering, drafting and clerical personnel in the Special Projects Section who withstood the pressure of too many deadlines and many revisions.

SECTION 1

CONCLUSIONS

The work performed under this demonstration grant has shown that it is possible to utilize friction-reducing chemicals to prevent or limit overflows in a working sewer line by establishing an automatic injection system for the materials. It has also been shown possible to increase the capacity of a "package" sewage lift station by injection of a slurry of friction-reducing polymer into the pump intake.

Three methods of polymer feed control were utilized in the demonstration work; constant rate, flow proportional, and level proportional. The first of the three is the simplest and least expensive in terms of equipment and has proven to be adequate under most conditions.

Polymer dosages directly from the dry material have been in the range of 15 to 50 parts per million, considerably below that used previously in large sewers. This fact engenders the possibility that polymer injection may be more economical than previously believed.

Two polymer types from two different manufacturers have been utilized; Union Carbide Polyox WSR-301 (polyethylene oxide) and ICI America 4430 (polyacrylamide copolymer). There are no noticeable differences in friction-reducing properties, but a considerable difference in mixing properties exists.

Two problems which have limited the usefulness of the polymer injection facility are instrumentation failures and polymer lumping. The first problem can only be resolved by the equipment manufacturers. The second problem, polymer lumping, has been solved by a re-design of the polymer feed-funnel to incorporate a trap for the lumps.

Insufficient data has been obtained to permit the production of a user's manual to permit general application of friction-reducing chemicals.

One type of polymer tested, ICI America 4430 polyacrylamide, has a wetted specific gravity greater than 1.0, thereby producing some polymer accumulations near the bottom of the mixing tank. Mechanical agitation with a slow speed paddle would make the injection rate more constant.

SECTION 2

RECOMMENDATIONS

It is recommended that the station continue to be operated for the purpose of controlling overflows in the study area and also provide the additional flow-head loss data desired.

A slow-speed mechanical stirrer should be added to the mixing tank to produce a more uniform slurry of the "difficult" materials.

SECTION 3

INTRODUCTION

SCOPE AND PURPOSE

The City of Dallas has been studying a means whereby the overflows from a sanitary sewer during periods of wet weather may be eliminated without resorting to expensive new construction or alteration. The means being studied is the addition of friction-reducing chemicals to a sewage stream in order to reduce the head loss caused by turbulent friction in the sewer pipe.

In order to demonstrate this phenomenon, a complete drainage area, the Bachman Creek watershed, was chosen as the study area under EPA Demonstration Grant 11020 DZU, with the goal being the elimination of overflows by the "as-required" automatic injection of the friction-reducing chemicals.

This report presents data gathered during the conduct of the program, between November 1, 1969 and April 15, 1974.

BACKGROUND

The Bachman Creek trunk sewer is a branched flow system consisting of approximately 45,000 feet of trunk line, 700,000 feet of collector lines (not including house laterals) which serves a drainage area of about 8,000 acres. The main trunk lines follow natural drainage channels and in most locations consist of unreinforced concrete pipe embedded in concrete poured in channels cut in the limestone bedrock. Access to the trunk lines is limited to personnel on foot except at those locations where a street crosses the line route.

During periods of heavy rainfall, water from either illegal connections, inflows, or infiltration enters the collection system to such an extent that the ultimate capacity of the line is exceeded. These excess flows are relieved through manholes and overflows constructed to protect the property owner along the trunk.

Because of the relative inaccessibility of the lines, and the fact that the existing line is adequate to carry normal dry weather flows, an alternative to reconstruction or construction of relief lines was preferable. Elimination of the entry of the wet weather flows into the system is the ultimate solution; an on-going infiltration/inflow abatement program is approaching this permanent solution by inspecting, re-engineering, repairing, and replacing the sewers in the area. However, the elimination of excess flows is a time-consuming process, and elimination of overflows in the interim period is necessary.

The background experimental work for the present program was reported in EPA Report, "Polymers for Sewer Flow Control," 11020 DIS, August, 1969. A comprehensive bibliography of other publications concerning the theory and practice of friction reduction is included in this report.

PROGRAM DESIGN

The program was divided into four phases, each of which generated data used as input in succeeding phases. The four phases were:

A. Study Phase - Instrumentation, analysis of the drainage system, computer modeling, and preliminary injection tests.

B. Design - Design of the injection station and its ancillary equipment.

C. Construction - Construction and check-out of the equipment.

D. Demonstration and Operation - Demonstration of polymer effectiveness, analysis of results for application elsewhere, and preparation of maintenance and operation documentation.

SECTION 4

POLYMERS AS TURBULENT FRICTION REDUCERS

HISTORY OF TURBULENT FRICTION REDUCTION

In 1948 a Dutch researcher named Toms noted that certain chemicals dissolved in water altered the flow characteristics of the fluid in a manner which could not be explained using classical mathematical techniques. Upon further investigation he found that the results obtained during the measurement of viscosity varied with the rate at which the fluid was sheared. That is, the viscosity was not a constant ratio of shear stress and shear rate.

This phenomenon, which later became known as the Toms' Phenomenon, remained a laboratory curiosity until it was "rediscovered" by companies working with fluids used for the stimulation of oil wells. Researchers using certain natural gums with the generic name "guar gums" for viscosity control found that a dilute solution of these gums in water exhibited lower friction losses in pumped systems thereby increasing the efficiency of such systems.

Because a guar gum was a natural polymeric material, a dramatic research effort in polymer chemistry was begun to discover even more efficient man-made materials.

Having successfully applied polymers to oil-field friction reduction, personnel at the Western Company of North America began looking for other areas in which friction losses were significant. Three additional applications of the phenomenon were found; the reduction of friction and noise for submerged projectiles (torpedoes), the reduction of friction on the hull of fast warships and the augmentation of flow capacities in pipes used for product transport, including sanitary sewage and stormwater. It is this last and most difficult application which is the subject of this manual.

THE NATURE OF TURBULENT FRICTION

Since most problems in sanitary collection systems arise when sewer pipes cease behaving as open channels, that is, when the cross section of the pipe is completely filled with the flowing fluid, the discussion of turbulent friction will be limited to full-pipe flow. In addition, since laminar flow so rarely occurs in practical sewer systems, flow in a laminar regime will be largely ignored except as a basis for discussion.

If one imagines a "perfect" fluid system, that is a pipe and fluid which is completely devoid of friction or other disturbing influence, each particle of fluid will move through the pipe exactly parallel to the walls of the pipe. This type of flow is illustrated by Figure 1. In this ideal system, the fluid molecules do not collide or interact with each other or with the walls of the pipe and there will be no energy transfer within the confines of the pipe. The velocity of every particle will be exactly equal to that of every other particle and the velocity profile will be shown in Figure 1. If we introduce energy into the fluid in this situation by sloping the pipe, as in Figure 2, it is easy to see that all the potential energy available will be converted to kinetic energy and we can write the specific energy equation.

$$\text{Potential Energy} = \Delta Z = \frac{V^2}{2g} = \text{Kinetic Energy} \qquad (1)$$

Where ΔZ= difference in height of the ends of the line referred to datum

V=velocity in fluid.

g= gravitational constant.

If the fluid particles are allowed to interact with each other and the pipe wall, but the particles are still required to travel parallel to the centerline of the pipe, we arrive at a flow which is illustrated by Figure 3. At the pipe wall, which is motionless, the fluid in contact with the wall is also motionless and the velocity of particles increases with increasing distance from the pipe wall until a maximum is reached at the pipe centerline. This condition approximates laminar flow. Under these conditions, there is friction loss, heat is generated throughout the fluid and at the pipe wall. This heat raises the temperature of the pipe and the fluid, and is not available for moving the fluid. Referring again to Figure 2, we must now write the specific energy equation as:

Figure 1. Velocity Profile for Fluid Flowing in an "Ideal" Pipe (friction factor = 0)

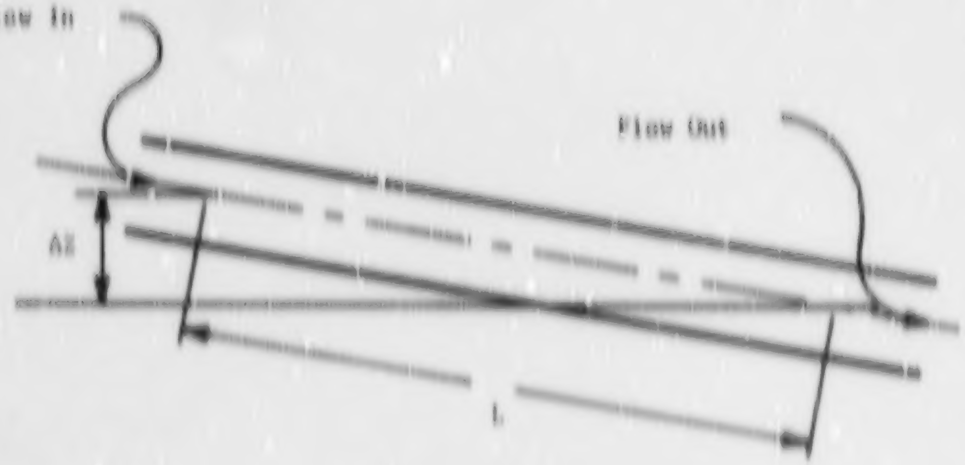
Flow In
Flow Out
ΔZ
L

Figure 2. Symbol Definitions for Gravity Flow in a Pipe

$$\text{Potential Energy} = \Delta Z = h_L + \frac{V^2}{2g} \qquad (2)$$

Where h_L is head loss in the same units as ΔZ.

The symbol h_L represents the energy lost as heat. The energy loss due th friction under laminar conditions is the minimum possible in a practical fluid system, and is generally used as a reference value for determining the effectivuness of friction reduction. Energy losses in laminar flow are larguly due to internal friction and increase in direct proportion to the viscosity of the fluid. For the purposes of d,scussion, these losses will be referred to as viscous friction.

The two cases of flow discussed above required that all of the fluid particles travel in straight parallel lines. In practical pipe flows it is found that this is rarely the case. Instead, when the fluid is viewed on a microscopic level, the particles appear to be in random motion, colliding with each other and the pipe wall. This is the condition which is called turbulence. When inspected on a microscopic scale the velocity profile can be illustrated as in Figure 4 . As in the previous case, the velocity of the individual fluid particles at the pipe wall is zero. However, unlike the previous case, higher velocities are found much nearer the pipe wall, and the central core of the flow exhibits a relatively uniform velocity.

The collisions that occur in this flow state generate heat at a higher rate than our laminar model because now we have more frequent contact between particles and the pipe wall and there are particles with velocities which are in directions which oppose the flow. In fact, a flow meter which responds rapidly to flow velocity will indicate as shown in Figure 5. Therefore, it may be concluded that turbulent losses are largely due to inertial effects.

If we write our specific energy equation for the turbulent case, and assume that one may differentiate between heat losses caused by viscous friction and turbulent, or inertialfriction, we have:

$$\text{Potential Energy} = \Delta Z = (h_L + h_T) + \frac{V^2}{2g} \qquad (3)$$

Where: The symbol h_T represents the energy lost because of turbulence. To simplify calculations the term in parenthesis generally written as h_f where:

$$h_f = h_L + h_T = \text{Total friction loss} \qquad (4)$$

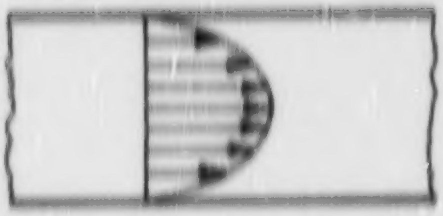

Figure 3. Velocity Profile for Fluid in the Laminar Regime
(Friction factor > 0)

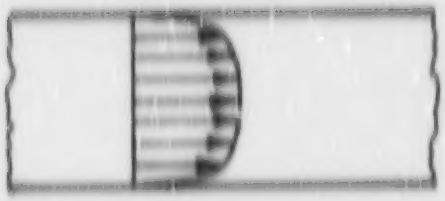

Figure 4. Velocity Profile for Fluid Flowing in the Fully-Developed Turbulent Regime
(Friction factor > 0)

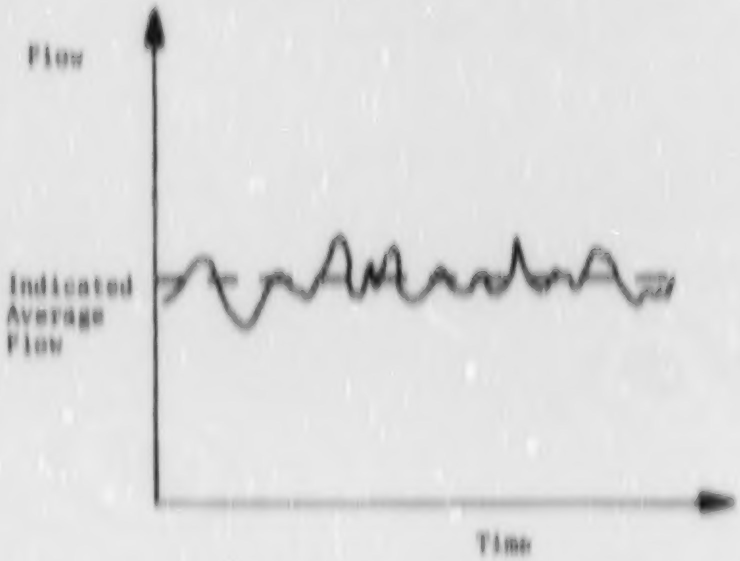

Figure 5. Typical Graph of the Output of a Rapid-Response Flowmeter Measuring Turbulent Flow*

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*Rouse, Hunter (ed.). Engineering Hydraulics. New York, John Wiley and Sons. Inc., 1950. p. 86.

The purpose of writing two terms is to emphasize the fact that the term "friction reduction" applies only to turbulent friction; that is, those losses attributable to inertial effects.

EFFECT OF POLYMERS ON ENERGY LOSSES

A great number of researchers have attacked the problem of determining the reasons that polymers dissolved in a fluid reduce turbulent friction losses. This research has resulted in many theories which range from the attenuation of turbulent eddies to the thickening of the laminar sublayer along the fluid-pipe interface. There have also been a number of attempts to predict the behavior of any material as a friction reducer, but the problem has proven so complex that practical applications of the phenomenon have relied almost entirely on the results of experimentation. It is for this reason that the writer will make no great effort to explain the mechanism of friction reduction; only the gross effect will be discussed.

The polymers used for friction reduction in water are obviously water-soluble, but they also have a number of other characteristics, which govern their behavior. First, the polymers have very high molecular weights; the more efficient materials have molecular weights in the range of 4,000,000 to 8,000,000. For comparison, the molecular weight of water is only 18. Some experimenters have had some success with materials with molecular weights as low as 500,000, but in general, these materials are less effective as friction reducers. A second necessary characteristic of the polymer materials is that their length to diameter ratio be large. There are many materials with high molecular weights which have low L/D ratios. More simply, not all polymers act as friction reducing agents. In fact, many high molecular-weight polymers have the opposite effect because they drastically increase the viscosity of the water and thereby increase viscous friction.

The logarithmic graph of Figure 6 is a typical example used for explanation.
The abicissa of this graph represents the total head loss for a given length of pipe, and the ordinate represents the flow rate through the pipe. The lower curve on the graph is typical of a head-discharge relationship for a gravity sewer pipe of moderate age, and can be represented by a power-law equation, that is:

$$Q=k\Delta h^n \qquad (5)$$

Where: Q = flow in convenient units

K = constant including length, diameter, and friction factor

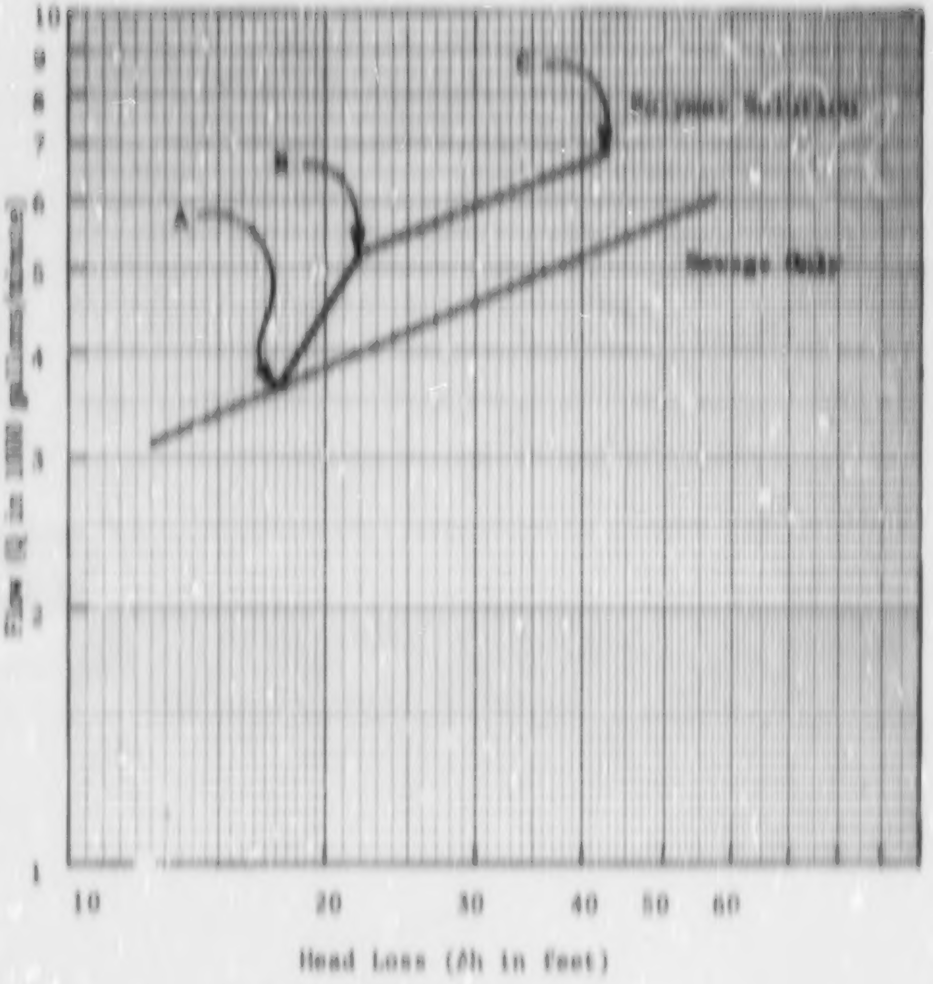

Figure 6. Graph Showing Typical Relationship
between Flow and Head Loss
in a Gravity Sewer
with and without Polymer Addition

Δh = head loss in convenient units

n = empirical exponent

If n = 0.5 the equation is similar to the Darcy-Weisbach equation,

$$\Delta h = f \frac{L}{D} \frac{V^2}{2g} \qquad (8)$$

and the friction factor, f, is a function of Reynolds' Number. If n = 0.54 the equation resembles the Hazen-Williams equation for flow in fullpipes. In the graph shown, n = 0.44. Since this coefficient cannot be found in any classical pipe flow formula, it indicates that the example pipe exhibits loss characteristics which cannot be reconciled with flow design equations. Measurements of flows and heads showed that this apparently anomalous behavior was the rule rather than the exception for sewer pipes in Dallas. The importance of determining the head-discharge relationship for a pipe before attempting friction reduction cannot be over-emphasized; if this relationship is not known the effect of friction reduction cannot be predicted or evaluated.

The upper curve in Figure 6 represents the effect of polymer addition to the flow in the pipe. This curve is typical of a moderately good friction-reduction polymer. Note that for a given head loss the flow is increased, or, conversely, for a given flow the head loss is decreased. In practical pipe systems, both effects usually occur simultaneously. It should also be noted that at the lower head losses, in this case below approximately 22 feet of water head, the apparent friction reduction is decreased, and the effect of polymer addition disappears at a head of about 17.5' of water. This fact is typical of all friction reducing agents.

Figure 6 is also typical of the behavior of friction reducing polymers in that the graph of the sewage flow with polymer addition is almost parallel to the graph of the sewage without polymers. This is true in the range of velocities practically obtainable in a gravity system. In pumped systems, however, it is easily possible to produce turbulence of such great magnitude that the physical structure of the polymer molecule is destroyed. When this occurs the two lines will converge at the upper end. The normal term applied to this phenomenon is "shear degradation."

By-passed in the discussion above was the reason for low friction reduction at low head losses. This is explainable in two parts; "onset shear stress" and "shear dependence of friction reduction." Studies by various researchers have shown that the polymers used as friction reducers do not become effective until some minimum shear stress at the fluid-pipe wall is reached. This minimum shear stress is called the "onset shear stress" and is a property of the particular polymer molecule. The shear stress at the wall of a pipe can be calculated using the geometric properties of the pipe and the head loss at any flow rate.

Figure 7 illustrates the derivation of wall shear stress. Consider a volume of any fluid of length L, bounded by a pipe of diameter D. On the upstream face there is a head of h +Δh acting, and on the downstream face a head of h. The following equation may be written:

$$(h+\Delta h)\ \left(\frac{\pi D^2}{4}\right) - (h)\ \left(\frac{\pi D^2}{4}\right) = (\tau_w)\ (\pi DL) \quad (7)$$

Where τ_w = shear stress at the pipe wall.

Reducing the equation,

$$(\Delta h)\ \left(\frac{\pi D^2}{4}\right) = \tau_w\ (\pi DL) \quad (8)$$

and

$$\tau_w = \frac{D\Delta h}{4L} \quad (9)$$

It should be remembered that Δh has a specific relationship to the flow in the pipe as defined.

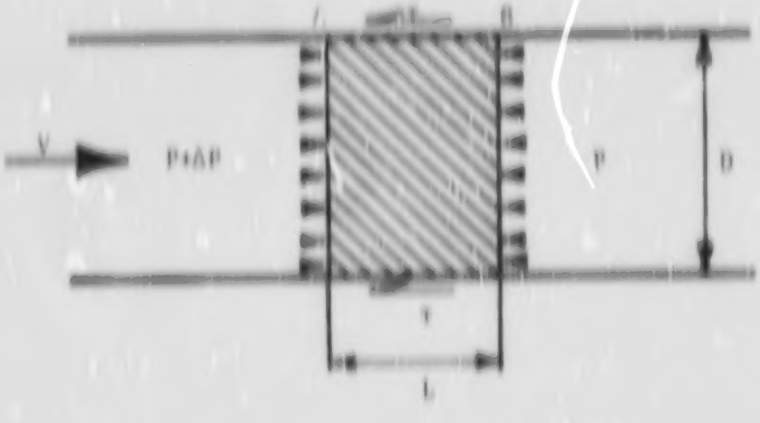

Figure 7 Element of Fluid Moving in a Pipe Showing Derivation of Shear Stress (τ)

A superficial inspection of the expression would indicate that the wall shear stress increases in proportion to pipe diameter. However, for a given flow the head loss (Δh) decreases with increasing pipe diameter. In fact, the head loss decreases at a rate proportional to the fourth power of the inverse ratio of the diameters of the two pipes, if the pipes have equal roughness and a relationship such as the Darcy-Weisbach equation is assumed. That is:

Assuming two pipes of diameters D_1 and D_2 of equal length L

Where $D_2 > D_1$

and $\frac{K_1}{D_1} = \frac{K_2}{D_2}$

$$\text{then } \Delta h_1 = KV_1^2 \qquad \text{(Darcy-Weisbach Equation)} \qquad (10)$$

and $\Delta h_2 = KV_2^2$

for a given flow Q,

$$V_1 = \frac{4Q}{\pi D_1^2} \text{ and } V_2 = \frac{4Q}{\pi D_2^2} \qquad (11)$$

$$\text{then } \frac{V_2}{V_1} = \left(\frac{D_1}{D_2}\right)^2 \qquad (12)$$

$$\text{Hence } \frac{\Delta h_2}{\Delta h_1} = \left(\frac{V_2}{V_1}\right)^2 = \left(\left(\frac{D_1}{D_2}\right)^2\right)^2 = \left(\frac{D_1}{D_2}\right)^4 \qquad (13)$$

The wall shears in the two pipes of different diameter can then be related.

$$\frac{(\tau_w)_2}{(\tau_w)_1} = \frac{D_2}{D_1}\,\frac{\Delta h_2}{\Delta h_1} = \left(\frac{D_2}{D_1}\right)\left(\frac{D_1}{D_2}\right)^4 = \left(\frac{D_1}{D_2}\right)^3 \qquad (14)$$

The above expression is important to a user, since it becomes obvious that a material which acts as a friction reducer in one pipe may not work in another pipe because the onset shear stress never occurs.

The shear dependence of friction reduction can be understood by considering the region between point "A" and point "B" on Figure 7. It is obvious that as the onset shear stress

(Point "A") is exceeded and friction reduction occurs, the magnitude of the friction reduction increases until some maximum is reached (Point "B"). Once this maximum occurs further increases in shear stress have little or no effect on friction reduction efficiency.

Therefore, for specific polymer solution in a specific pipe, there is a range of flows in which there will be no friction reduction, a range of flows of which the efficiency of friction reduction will be related to the flow rate, and there is a third range over which the friction reduction efficiency is independent of the flow rate. Obviously it would be desirable to always operate in the most efficient range. However, in gravity sewer systems this will not always be possible, and as has been discussed above, there can be flow and head loss conditions under which friction reducing techniques cannot be applied.

MAGNITUDE OF FRICTION REDUCTION EFFECT

In the previous section it was pointed out that under certain conditions the addition of polymers to a gravity sewer line can cause either increased flows, decreased head losses, or both effects can occur together. No mention of the magnitudes of these effects has been made thus far. This section discusses the definition of friction reduction, the theoretical limits of friction reduction, and the probable maximums which can be expected under field conditions.

The definition of friction reduction utilizes the concept of friction factor reduction, and bases a percentage change on a comparison of friction factors in turbulent flow with the imaginary extension of the laminar friction factor graph. In the form of an equation, percentage friction reduction is:

$$\psi = \left(\frac{f_t - f}{f_t - f_l}\right) x\ 100 \qquad (16)$$

Where ψ = percentage friction reduction

f_t = friction factor of fluid in a pipe

f = friction factor of fluid with friction-reducing agent added

f_l = projected laminar friction factor

R = Reynolds number (constant)

The laminar friction factor is defined by

$$f_l = \frac{64}{R} \qquad (16)$$

Where R = Reynolds number

At the Reynolds Numbers of fully developed turbulent flows in large pipes, the quantity represented by f_l is sufficiently small as to be negligible. The friction reduction equation can be reduced to:

$$\psi = (1 - \frac{f}{f_t}) \times 100 \qquad (17)$$

For any specific pipe at a given flow velocity, head loss measurements can be used to arrive at friction reduction efficiencies directly:

$$\psi = (1 - \frac{\Delta h}{\Delta h_t}) \times 100 \qquad (18)$$

Where ψ = percentage friction reduction
Δh = head loss with polymer added
Δh_t = head loss without polymer

This form of the expression has previously been used by Savins*.

It is obvious then that the prediction of a friction factor is the only step necessary in order to predict a friction reduction efficiency and the head loss-flow relationship. One would then be able to engineer a solution to a friction-reduction problem. However, the prediction of the appropriate friction factor is the stumbling point of the technology, since the friction factor of a dilute polymer solution is a function of the following parameters:

1. polymer characteristics
2. wall shear stress
3. velocity of flow
4. diameter of pipe

Seyer and Metzner** have suggested a form for the friction factor equation as follows:

---

*Savins, J. G. A Stress-Controlled Drag Reduction Phenomenon, Rheologica Acta, (Darmstadt), 6:4, 1967

**Seyer, F.A. and A.B. Metzner, Drag Reduction in Large Tubes and the Behavior of Annular Films of Drag-Reducing Fluids, Canadian Journal of Chemical Engineering, (Ottawa), 47:, Dec. 1969

$$\frac{1}{\sqrt{f}} = \frac{(1-\xi)^2}{\sqrt{2}\;2}\left[A\ln\left(\frac{R}{2}\sqrt{f}\right) + B(\theta) - A\ln 2\sqrt{2}\right] - \frac{G}{2\sqrt{2}} \qquad (19)$$

Where f = Darcy friction factor

A= slope of the logarithmic velocity profile at the laminar sublayer boundary

R= Reynolds Number

$B(\theta)$ = intercept function for logarithmic velocity profile

θ= dimensionless relaxation time of polymer molecule

G= Empirical function, approximated by G= 3.0 for design purposes

ξ= dimensionless distance from pipe wall= y/r (r= radius of pipe, y= distance from pipe wall)

The above equation reduces to the Nikuradse equation for smooth pipes for a Newtonian fluid for which $B(\theta) = 5.6$, $\xi = 0$, A= 2.46, and G=3.0. However, it is not possible to use the above equation without a great deal of information including the definition [illegible], y, and $B(\theta)$. These terms are interrelated by additional equations. The parameter ξ, is defined as the ratio of the thickness of the laminar sublayer (near the pipe wall) to the radius of the pipe. The value of ξ ranges from almost zero to about 0.2 and can be determined from the relationship:

$$B(\theta) = \left(y \times \sqrt{\tau_w/\rho} \times \frac{1}{\nu}\right) - A\ln\left(y \times \sqrt{\tau_w/\rho} \times \frac{1}{\nu}\right) \qquad (20)$$

and

$$\xi = \frac{y}{r} \qquad (21)$$

Where y = distance from pipe wall of the intersection of the linear and logarithmic profile approximations

τ_w= fluid shear stress at the pipe wall

ρ = fluid density

ν = apparent kinematic viscosity

r = radius of pipe

The function $B(\theta)$ is a characteristic of the polymer solution being considered and the wall shear stress, but Seyer and Metzner have postulated that the function is identical for all non-

Newtonian polymer solutions. Their plot of $B(\theta)$ as a function of θ is shown in Figure 8. Assuming that their supposition is correct, all that remains in the solution of a friction reduction problem is to determine the relaxation time, θ, for the polymer solution under the flow conditions of interest.

Previously mentioned was the fact that dilute polymer solutions generally behave according to a "power law", that is, the shearing stress in the fluid is proportional to the shear rate raised to some power which will range from 0.0 to 1.0 for "real world" fluids. Therefore, it can be shown that the relaxation time, θ, is proportional to the shear stress, or:

$$\theta = K\ \tau_w^n \tag{22}$$

Where θ = relaxation time

K = constant of proportionality

τ_w = fluid shear stress at the pipe wall

n = a value to be evaluated by experiment

The suggested method for the evaluation of a potential friction reducing material is to run small scale experiments in which head loss and flow may be accurately measured for the polymer concentration of interest. A friction factor may then be calculated and inserted into Equation (19) along with the appropriate Reynolds Number. As a first approximation the dimensionless number ξ may be assumed equal to zero. A value of $B(\theta)$ can then be determined. Using the graph of Figure 8, a corresponding value of θ can then be estimated. A logarithmic plot of θ versus τ_w may then be constructed, and the value of the constants K and n in Equation (22) computed. In order to refine the procedure, a few iterations through Equations (19), (20), and (21) will suffice to determine the value of ξ.

If the procedure outline above is repeated at a number of different polymer concentrations, it will then be possible to graph or tabulate the various parameters necessary to predict the friction factor and hence the friction reduction efficiency for the flow condition of interest.

As an estimate of the maximum friction reduction possible with water-soluble polymers, the maximum and minimum values which the function $B(\theta)$ can take may be applied directly in Equation (19) for a typical flow condition. Using a Reynolds Number of 1×10 which approximates the flow of water at 70° Farenheit through a 24 inch diameter pipe at 5.3 feet per second, the maximum and minimum values of the friction factor are:

Maximum f = 0.0112 Minimum f = 0.0030

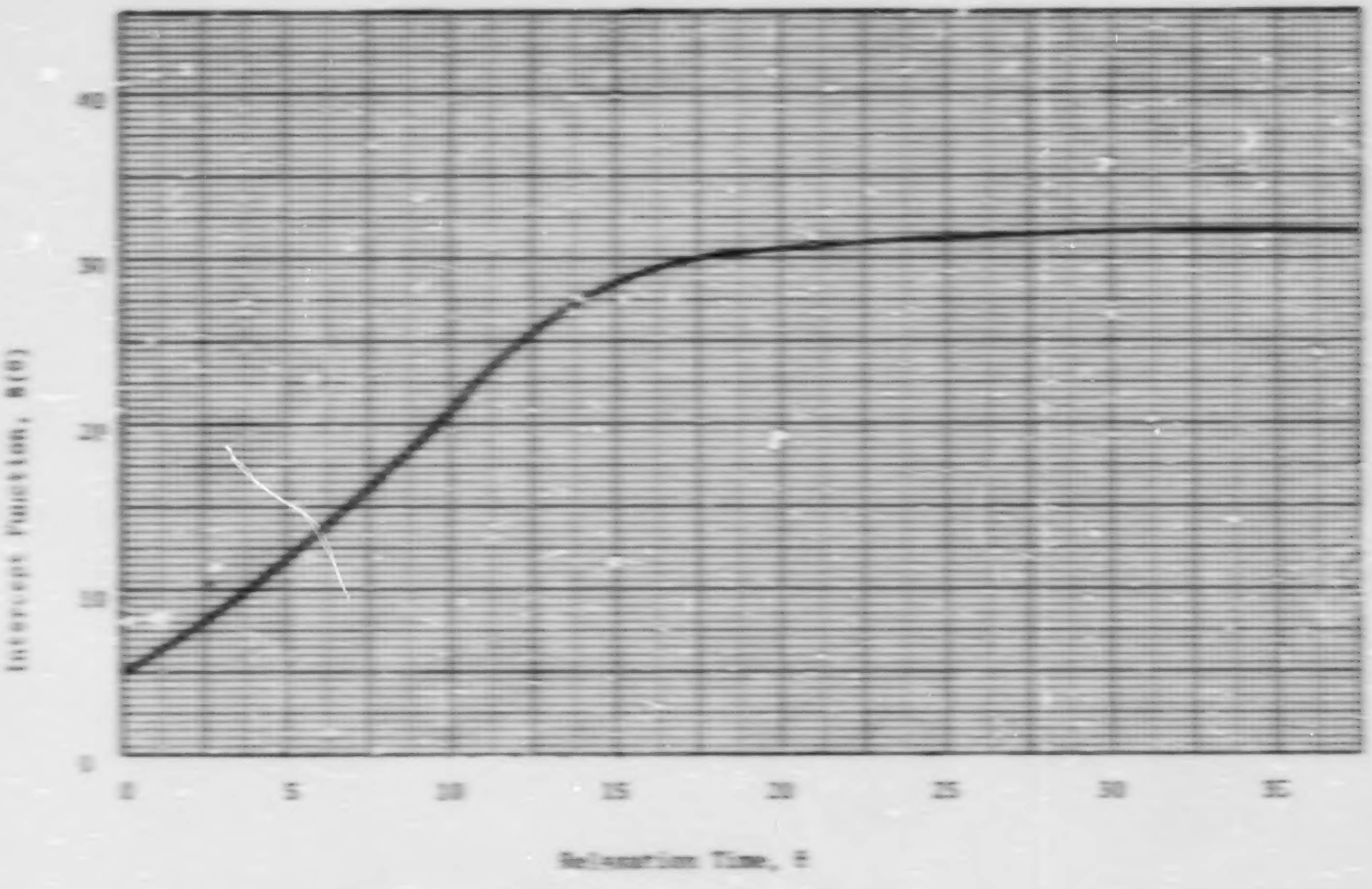

Figure 8. Graph of the Relationship Between The Logarithmic Profile Intercept Function and Dimensionless Relaxation Time

From Equation (17) the maximum friction reduction efficiency for the case cited is then equal to 73 percent. Studies have indicated that the maximum possible friction reduction is in the vicinity of 80 percent, so that a material which would behave as in the example above would be very satisfactory. Unfortunately, most successful polymer applications in gravity systems have shown maximum efficiencies in the range of 40 to 50 percent.

CALCULATIONS OF REAL PROBLEMS

Equations 18, 19, 20, 21 and 22 as presented in the preceding discussion work well when applied to "ideal" pipes in the laboratory. However, some problems arise when these equations are translated to practical applications; therefore a modification is indicated. Since the equations have been fitted to empirical models of velocity profiles during their development, these needed modifications are logically related to empirical information gathered in full-scale field tests, and although they have been checked against field-gathered data, additional testing will be necessary before they will become a standard of the industry.

The major problem encountered is one mentioned previously concerning the failure of actual gravity sewers to perform according to the textbook formulas. In checking Equation (18), it was found that although it becomes the Nikuradse equation when the proper constants are used, the Nikuradse equation did not predict the friction factors actually measured. For this reason it was necessary to first "fit" the equation to the encountered Newtonian flow conditions before it could be used to predict Newtonian parameters.

Re-writing Equation (19) in a reduced form we arrive at the following:

$$\frac{1}{\sqrt{f}} = (.3536)\,(1-\xi)^2\,\left[2.46\ \ln\ \left(\frac{R\sqrt{f}}{5.6568}\right) + B\,(\theta)\,\right] - \frac{G}{2\sqrt{2}} \qquad (23)$$

The symbols are as previously defined. If it is assumed that B (θ) is a unique function of the polymer material and concentration, and hence of relaxation time, then its value in the equation is fixed, as is the Reynolds Number of the flow (neglecting small changes in solution viscosity). However, if we inspect the constant symbolized by "G", it is found that the friction factor may be adjusted to fit data by varying the value of G. Hence, if the characteristics of a pipe transporting sewage can be measured so that the friction factor and Reynolds' Number for a few conditions are determinate, a value of G may be picked which will satisfy the data. The new value may then be utilized to predict the effect of friction reduction on that particular pipe. One caution in this respect is that it is conceivable that "G" could become a function of Reynolds Number in some cases.

SECTION 5

SELECTION OF MATERIALS FOR FRICTION REDUCTION APPLICATIONS

Section 4 of this report dealt with the problem of predicting the effect of polymers on a sewer line, and, as an adjunct, discussed a mythod for extrapolating laboratory data to field problem scale. This section presents typical data that might be generated in a laboratory,accompanied by the extrapolated data described in the preceding discussion.

During the course of the friction-reduction investigation in Dallas, thirty polymer products from eight different manufacturers were thoroughly tested in the laboratory to determine their friction-reducing properties. Of the materials tested, eighteen were considered efficient enough for serious consideration. The screening tests were performed in an apparatus illustrated by Figure 9. The test sections which consisted of tubing of various diameters were very carefully fabricated to give conditions as near ideal as possible. The tests were performed as outlined below.

A sample of the test material was dissolved in de-ionized water in the manner prescribed by the manufacturer in the proportions required to give the required concentration of active friction reducer. This solution was gently agitated for a sufficient length of time to insure a clear solution with no lumps or "fish-eyes". Materials were tested immediately after solution agitation. Made-up solutions were not tested more than once or retained longer than 30 hours.

Two gallons of the solution prepared as above were placed in the pressure vessel with valve (F) in closed position. With the pressure vessel open to atmospheric pressure, valve (F) was then opened slightly until the tube (C) and fittings were purged of air bubbles. Valve (F) was then closed.

Static pressure was built-up in the pressure vessel by means of an auxiliary pressure regulator and air or nitrogen source. The applied pressure was adjusted between 10-160 psi.

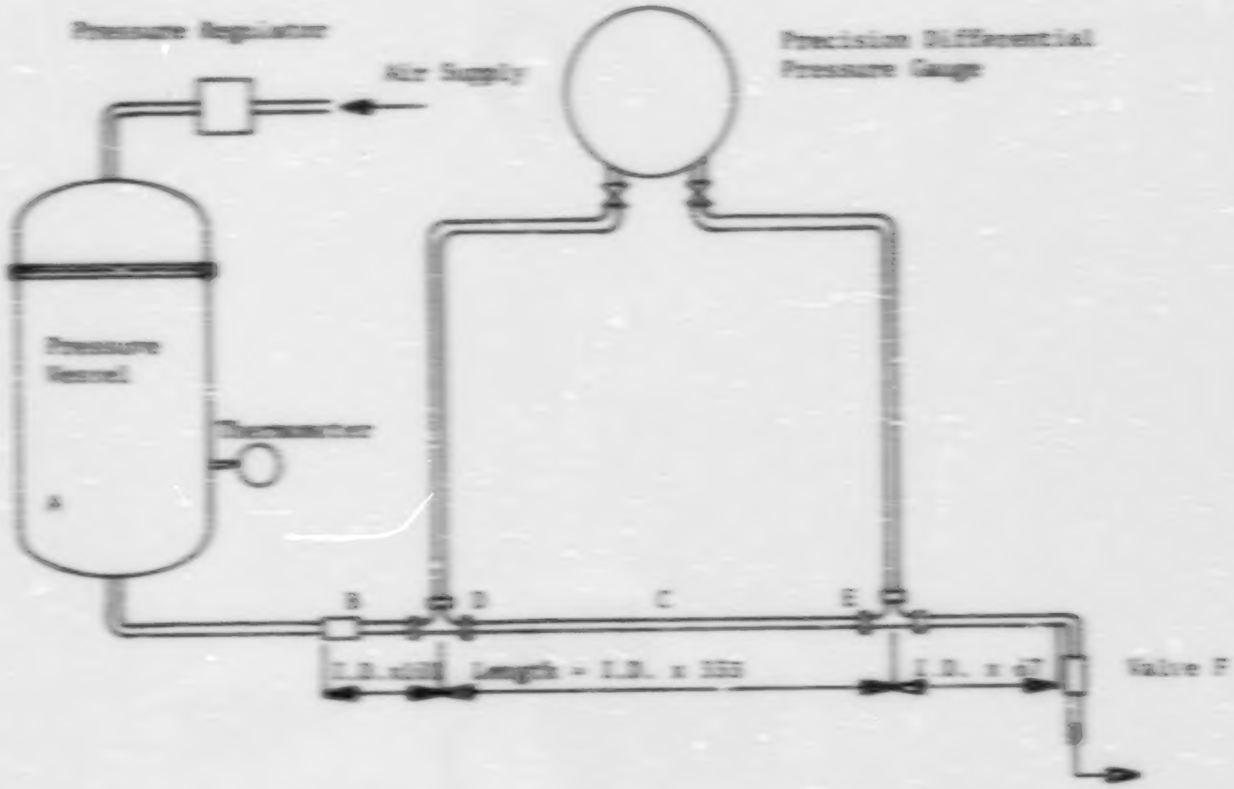
Pressure Regulator
Air Supply
Precision Differential
Pressure Gauge
Pressure
Vessel
Thermometer
A
B
D
C
E
I.D.x100
Length = I.D. x 333
I.D. x 67
Valve F

Figure 9 Diagram of Apparatus for Screening Friction-Reducing Materials

TABLE 1

*LABORATORY AND REDUCED DATA FOR POLYOX WSR-301 AT A CONCENTRATION OF 10 wppm**

Velocity (fps)	Reynolds Number	Friction Factor	τ_w (psf)	α	$\sqrt{\tau_w/\rho}$ (fps)	$B(\alpha)$	Ψ (%)
13.86	21021	.0118	.551	6.5	.533	14.6	55
21.49	32549	.0096	1.08	7.6	.746	16.3	59
27.19	41184	.0090	1.63	7.8	.917	16.7	59
30.86	46749	.0093	2.16		1.06		56
34.45	52190	.0092	2.65		1.17		56
37.71	57113	.0092	3.19		1.28		55
40.58	61462	.0093	3.73		1.39		54
43.59	66020	.0094	4.32		1.49		52
45.68	69189	.0095	4.81		1.57		51
48.35	73234	.0095	5.40		1.66		50
49.90	75676	.0097	5.89		1.74		49
50.81	76958	.0098	6.10		1.77		49

*Data taken in a 0.18 inch diameter test facility.
**Weight parts per million.

TABLE 2

*LABORATORY AND REDUCED DATA FOR POLYOX WSR-301 AT A CONCENTRATION OF 50 wppm**

Velocity (fps)	Reynolds Number	Friction Factor	τ_w (psf)	θ	$\sqrt{\tau_w/\rho}$ (fps)	$B(\theta)$	ψ
18.25	27644	.00684	0.551	11	.533	22.4	72
22.33	33821	.00624	0.756	11.5	.624	23.7	73
30.98	46931	.00556	1.30		.819		74
35.37	53576	.00536	1.62		.914		74
39.97	60541	.00578	2.05		1.03		74
45.16	68407	.00524	2.59		1.16		73
51.46	77949	.00496	3.19	13	1.28	26.3	74
54.50	82555	.00516	3.73		1.39		72
58.20	88166	.00524	4.32		1.49		71

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*Data taken in a 0.18 inch diameter test facility.

**Weight parts per million.

TABLE 3

*LABORATORY AND REDUCED DATA FOR POLYOX WSR-301 AT A CONCENTRATION OF 100 wppm**

Velocity (fps)	Reynolds Number	Friction Factor	τ_w (psf)	θ	$\sqrt{\tau_w/\rho}$ (fps)	B(n)	ψ (%)
5.31	8036	.01584	0.108	5.6	.236	12.8	53
9.08	13759	.01080	0.216		.334		63
12.02	18208	.00924	0.324	9	.409	18.6	66
15.45	23397	.00784	0.454		.484		69
17.72	26841	.00704	0.538		.525		72
22.08	33448	.00640	0.756		.624		73
25.98	39335	.00596	0.972		.708		74
29.88	45264	.00548	1.19	12.75	.783	25.9	75
33.31	50450	.00524	1.40		.850		75
36.01	54547	.00512	1.74		.947		75
41.87	63423	.00508	2.16		1.06		75
47.58	72072	.00492	2.70		1.18		75
52.59	79659	.00468	3.13		1.27		75
59.95	90811	.00428	3.73	16.5	1.39	29.6	77

*Data taken in a 0.18 inch diameter test facility.
**Weight parts per million.

TABLE 4

*LABORATORY AND REDUCED DATA FOR PERCOL 155 AT A CONCENTRATION OF 10 wppm**

Velocity (fps)	Reynolds Number	Friction Factor	τ_w (psf)	θ	$\sqrt{\tau_w/\rho}$ (fps)	$B(\theta)$	ψ (%)
18.41	27880	.00664	0.546	11.3	.530	23.3	73
26.50	40137	.0064	1.09	11	.750	24.0	71
31.06	47057	.00684	1.60		.908		68
34.84	52779	.00732	2.16		1.06		65
37.67	57059	.00784	2.70		1.18		62
40.68	61612	.00796	3.19		1.28		60
42.94	65043	.00844	3.78		1.40		57
44.57	67517	.00884	4.27		1.48		55
47.02	71224	.00896	4.81		1.57		54
49.36	74799	.00937	5.51		1.69		51
50.17	75992	.01044	6.37		1.81		45

*Data taken in a 0.18 inch diameter test facility.

**Weight parts per million.

TABLE 5

*LABORATORY AND REDUCED DATA FOR PERCOL 155 AT A CONCENTRATION OF 50 wppm**

Velocity (fps)	Reynolds Number	Friction Factor	τw (psf)	θ	$\sqrt{\tau_w/\rho}$ (fps)	B(θ)	ψ
18.50	28026	.00636	0.529	11.0	.522	24.2	74
29.79	45123	.00500	1.08	14.3	.746	27.9	77
38.43	58212	.00462	1.62	16.3	.914	29.4	78
43.49	65877	.00448	2.05	18	1.03	29.3	77
50.41	76363	.00423	2.65		1.17		77
56.50	85590	.00412	3.19	19.8	1.28	30.5	78
59.83	90630	.00412	3.56		1.36		78
65.98	99949	.00404	4.27	21	1.48	30.7	77

*Data taken in a 0.18 inch diameter test facility.

**Weight parts per million.

When the above preparations were completed, a "run" was made by opening valve (F) a preselected amount, measuring the steady-state flow and frictional pressure loss (as indicated by the differential pressure gauges).

Three tests were performed at a minimum of three different flow rates, with fresh solution used for each run, and the results at each flow rate were averaged for reporting purposes.

Three generic groups of polymer materials tested in the above manner are polyethylene oxides, polyacrylamides, and polyacrylamide co-polymers. The most efficient of each generic type were tested in full-scale field tests. These were:

Designation	Type	Manufacturer
Polyox WSR-301	Polyethylene Oxide	Union Carbide
Percol 155	Polyacrylamide	Allied Colloids
4430	Co-Polymer	ICI America

The first two materials are presently available from their manufacturers, but unfortunately production of the third material has ceased. The laboratory and calculated data for the materials which are still available appears in Tables 1 through 5. All spaces in the tables are not filled because inspection of the data shows that the materials do not behave as "power law fluids" over the full test range. Inspection of the tabulated wall shear stresses produced under these test conditions indicate that the polymer solutions suffered from shear degradation at the high velocities.

Table 6 lists the physical properties which were used in calculating the friction reduction parameters. Any dimensionally homogeneous set of units may be utilized, so long as they are used in all calculations.

TABLE 6

PHYSICAL CONSTANTS UTILIZED

FOR CALCULATIONS

IN TABLES 1 THROUGH 5

ρ=density of water=1.9380 slugs/cubic foot

ν=Kinematic viscosity=1.059 square feet/second

g=gravitational constant=32.2 feet/second^2

w=specific weight of water=62.43 pounds/cubic foot

To make comparison of the materials simpler, Figure 10 is a graph of θ (relaxation time) versus τ_w (wall shear stress) for the various solutions. Using this graph, it is possible to calculate the constants, K and n, to be used in Equation (22). The constants determined in this manner are displayed in Table 7.

TABLE 7

CONSTANTS FOR USE IN
THE EQUATION $\theta = K\tau_w^n$
FOR VARIOUS SOLUTIONS

Polymer	Concentration (wppm)	K	n
WSR-301	10	1.97	.1680
WSR-301	50	11.96	.1405
WSR-301	100	11.90	.248
Percol 155	10	11.03	-.0325
Percol 155	50	13.72	.293

The values of K and n for the Percol 155 at 10 wppm are doubted, since the sign of n would indicate that that solution gets more efficient as shear decreases.

An inspection of Figure 10 illustrates one weakness of scaling from laboratory results. In order to produce pressure drops which can be accurately determined, it is necessary to operate the short tube used at much higher shear stresses than those normally encountered in a gravity sewer system. For comparison, an 18 inch diameter sewer line with a hydraulic gradient of 0.77 percent only develops a wall shear stress of 0.18 pounds per square foot compared to the lowest average shear utilized in the laboratory of 0.56 pounds. Laboratory tests should be designed to cover the range of shear stresses which are expected in large-scale applications.

Figure 10 indicates that the Percol 155 material at a concentration of 50 weight parts per million(wppm) is more efficient than Polyox WSR-301 at a concentration of 100 wppm. This conclusion is correct under laboratory conditions. However, the Percol was found to be more difficult to disperse in the large scale equipment eventually constructed. It was found that additional mixing energy and water was required to form a good dispersion that was pumpable. One other significant difference is the respective onset shear stresses of the two materials. The onset point for Polyox has been found to be concentration dependent and is on the order of .012 pounds per square foot at 10 wppm and .038 pounds per square foot at 50 wppm. The onset point for polyacrylamides is relatively independent of concentration and occurs at a shear stress of about .06 pounds per square foot. Therefore at very low shears the Polyox will be a more efficient friction-reducing agent. However, both materials are suitable under the proper conditions.

If the materials for which data is given are chosen as a friction reduction material, the data may be used directly. The fact that only two types are described should not present a limitation to a potential user. In many cases, the manufacturer of a potential material can provide the data required for evaluation in the manner described, or a moderate investment can equip a wastewater treatment laboratory to perform the required tests.

Based on a potential user's specific requirements, the choice of a friction reducing agent should be made after evaluation of the following properties:

1. The onset shear stress should be lower than that anticipated in the "real world."
2. The material should not produce gross solution viscosity changes at low concentrations.
3. The material should work efficiently as a friction-reducing agent in the laboratory tests.
4. The material should be as "dispersible" in water as possible.

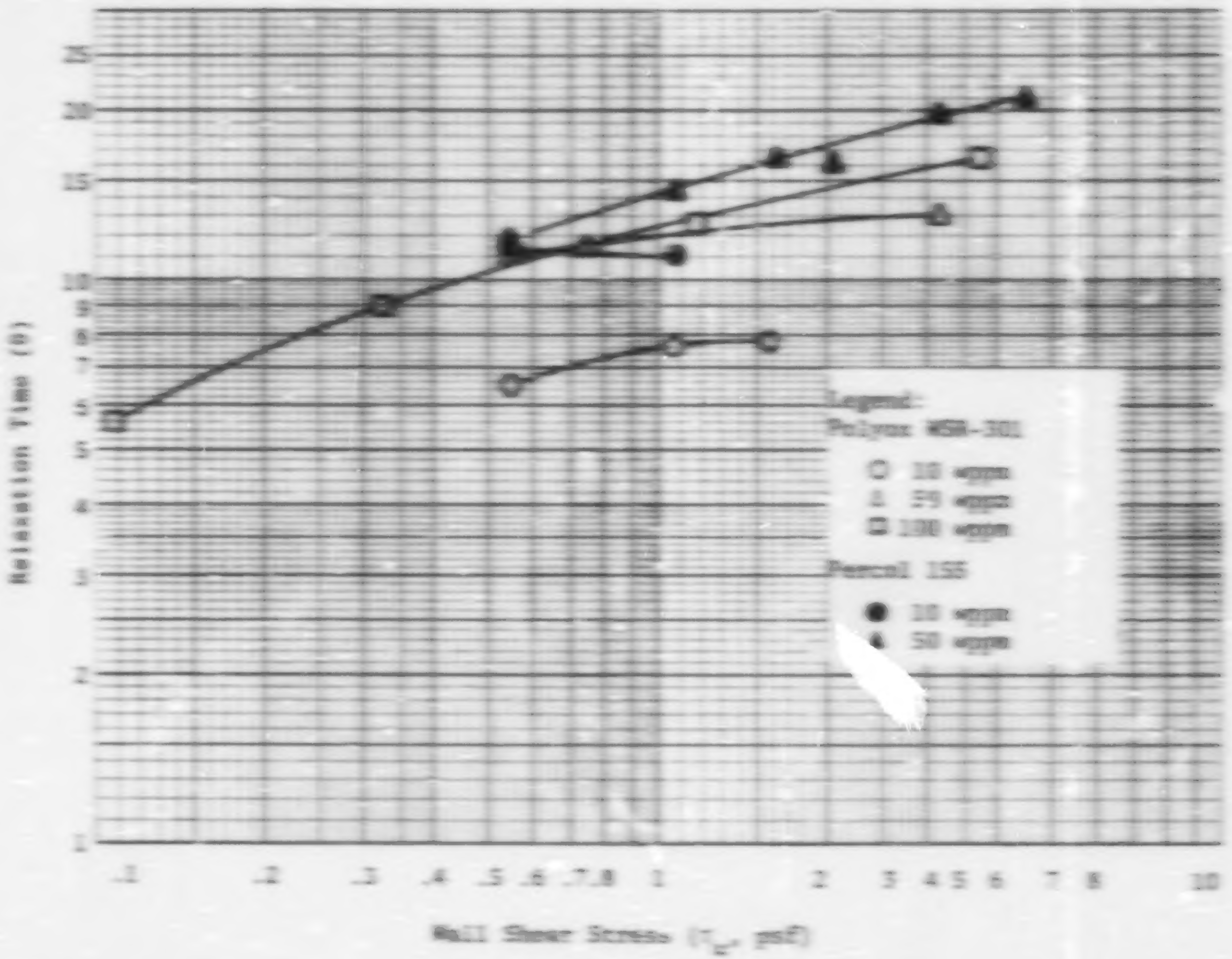

Figure 19. Graph of Relaxation Time Versus Wall Shear Stress for Various Concentrations of Percol 155 and Polyox WSR-301

PREPARATION OF POLYMER MATERIALS FOR INJECTION TESTS

During the course of the present and past projects, many products suitable for use as friction reducing materials have been tested and characterized. Appendix A is a list of presently known acceptable polymer[*] (I) materials, along with the manufacturer's name.

To obtain the polymer material used during the course of the present project, all those manufacturers were invited to submit a bid for any polymer material which complied with a supplied performance specification. The specification is included in this report as Appendix B.

The only material used during the preliminary tests was Polyox WSR-301, supplied by Union Carbide. The material was low-priced and exhibited friction reduction properties which approached the theoretical maximum of 80% when tested in the laboratory apparatus.

The polymer was delivered as a dry, granular material which required protection from moisture, bacteria, and heat. The portable equipment which was available for injection required that the polymer be mixed in a nonsolvent as a slurry for dispensing. During earlier work[**] the slurry was made by making a gel of isopropyl alchol and then suspending the friction reducing polymer in the resulting viscous media. This approach was initially used for this project; however, the slurry separates after two to three days leaving the liquid phase supernatent. In addition, the anhydrous alcohol used constituted a fire and explosion hazard.

These undesirable properties were not significant during earlier field work, since the polymer slurry was generally expended within 24 hours of preparation. However, the execution of work described in this report was dependent on rainfall events, requiring that thw polymer materials be prepared and stored until needed. It was therefore necessary to devise a stable material for the application.

The first attempt to produce a more stable slurry material consisted of the polymer mechanically mixed with a 40-percent sodium hydroxide solution. This slurry was stable for periods up to one week, but soon separated leaving the liquid phase sub-natant. Another disadvantage of this material is the obvious hazard of the caustic material to personnel and equipment.

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[*] Products forming micellar structures are not included.

[**] The Weston Co., "Polymers for Sewer Flow Control," USEPA Report No. 11020DIG08/69, August, 1969.

The final slurry material prepared for injection made use of the fact that the polymer being used, polyethylene oxide, is insoluble in saturated brine. The brine was prepared from rock salt and was relatively inexpensive. It is possible to form chemical complexes in the brine to suspend the polymer particles for extended time periods. Slurry of this type was made up in steel drums for handling convenience and stored for up to four months with only slight degradation of friction reduction ability caused by storage in the wet form. However, the slurry concentration changed during storage as evidenced by a clear sub-natant fluid. When the slurry was used for subsequent injections, grab samples of the slurry were used to determine slurry concentration.

The slurry used for the preliminary tests may be prepared in the following manner:

A. Measure thirty gallons of super-saturated sodium chloride brine into a standard 55-gallon drum.

B. Heat the brine to approximately 150° F.

C. Stirring gently, sprinkle in one pound of Hercules polymer FR-4 and one pound of Tamol (wetting agent).

D. Stir until the FR-4 polymer is completely dissolved.

E. Allow the brine-polymer solution to cool to approximately 85° F.

F. Increase the agitation of the polymer solution until a large vortex is formed.

G. Slowly add the dry polymer to be suspended, continuing agitation and rotating the drum to insure a uniform slurry. The maximum amount of polymer which can be suspended is dependent on the bulk density of the material and ranges from about 80 pounds for the low bulk density material to 100 pounds for material with a high bulk density.

H. Without stopping the agitation add 860 milliliters of saturated chromium chloride solution made by adding an excess of the chemical to saturated brine.

I. Stir until the color is uniform, or for about 3 minutes, and withdraw the stirrers. Excessive stirring will destroy the suspending properties of the slurry.

J. Transfer of the finished slurry to other containers should be by decanting, since pumping can break the slurry.

The proper preparation of this slurry material is largely an art and those not skilled in its preparation may find it difficult to produce a stable product on the first attempt. The above described slurry is only suitable for the polyethylene oxide materials or other materials insoluble in saturated brine.

Three possible disadvantages to the slurry prepared as above are inherent in its properties:

A. The slurry is extremely stable and requires mechanical dispersion to insure adequate solution in the treated line.

B. The brine used in the preparation may be objectionable in the event that chlorides are a local water quality problem.

C. The chromium ion used for complexing could become a significant pollutant if large quantities of the slurry were used.

SECTION 6

EQUIPMENT FOR POLYMER INJECTION

GENERAL STATEMENT OF THE PROBLEM

The water-soluble polymers used for friction reduction are furnished as dry granular solids which must be dissolved in the sewage in the correct proporations to produce the polymer-sewage concentration which has been previously determined. Because of certain characteristics of the polymer materials, it is not possible to simply "stir in" the solid polymer as one might add sugar to coffee. It is necessary to provide a means for effecting the dispersion and subsequent solution of the material. Although this particular requirement is the most critical stage of polymer injection, there are other requirements which must be met in the design of a polymer injection facility. These requirements include:

1. Handling of packaged polymer materials.
2. Environmentally-controlled storage of polymer material.
3. Metering of dry polymer solids.
4. Dispersion of polymers into water.
5. Injection of dispersed polymer into sewer line.
6. Control of polymer injection process.

This section of the report will present design factors which must be considered in assembling a polymer injection facility, and specific recomandations concerning equipment which has been shown effective in field tests will be made.

The polymers used for friction reduction are varied in chemical composition, but share certain significant physical characteristics. It is these physical characteristics which determine the manner in which they are applied. The common physical characteristics are as follows:

1. Solubility - The polymers used for friction reduction are very soluble in water, but the viscosity of the resulting solutions restricts the polymer-water ratio to low values if a pumpable fluid is required.

2. Molecular Weight - The molecular weight of those polymers found most effective range upward from three million. The molecular weight of water is only 18.

3. Physical Size - The extremely high molecular weights of the polymer materials are paralleled by the physical size of the molecules. For instance, a molecule of a polymer with a molecular weight of 4,000,000 is approximately .0012 inches long, and should apparently be visible to the naked eye. However, it is only 12 X 10^{-9} inches in diameter.

4. Physical Form - Polymers for friction reduction are granular, flake, or powder form material. The individual particles may be spheres, platelets, or discs which are made up of entwined individual molecules. These dry molecules can be likened to tightly-coiled springs with projections spaced along the coils at regular intervals.

5. Specific Gravity - The specific gravity of most water-soluble high molecular weight polymers fall into the range 0.98 to 1.08, which makes them neutrally buoyant.

6. Bulk Density - Air becomes trapped between the particles producing bulk densities on the order of 11 to 60 pounds per cubic foot with a mean value of about 25 pounds per cubic foot.

Two conditions necessary for complete solution of water-soluble polymers are:

A. Each polymer particle must initially be surrounded by enough water to satisfy the water uptake requirements of all the polymer molecules which constitute the particle, and

B. Once wet, the polymer particles must be kept physically separated until solution is complete.

If these two conditions are not met the individual polymer particles will agglomerate into sticky lumps which are externally wet with essentially dry centers, normally called "fisheyes." These fisheyes are very difficult to dissolve and will not go into solution quickly enough to act as friction reducers when injected into the sewer line.

PORTABLE FIELD TEST INJECTION EQUIPMENT

Earlier sewer line injection tests* were conducted using a pump to lift a portion of the sewage stream and force it through an eductor which provided a decreased pressure to feed the polymer slurry. The system worked well in those tests because the equipment could be placed immediately adjacent to an entry into the line (Figure 11) and suction and discharge hoses could be short. However, those points selected for injection for the present project were either totally inaccessible for the trailer-mounted equipment or the hose lengths involved (75-100 feet) were impractical.

The first modification to the equipment consisted of replacing the gravity feed on the slurry trailer with a positive displacement pump with a variable speed drive. The slurry could then be pumped into an eductor in which a stream of water from a fireplug provided the mixing energy required (Figure 12). Through additional experimentation, it was found that a good slurry could be adequately dispersed by the turbulence of the sewer into which the injection was made. The equipment was then simplified as shown in Figure 13, eliminating the need for a water source and the resulting long water hoses. This system was used for the first and second injection tests.

During the second injection test attempt, a shear pin in the pump broke while the slurry line (75 feet) was full. Water was absorbed through the injection nozzle and the hose plugged. When the pump was repaired and restarted the resulting high pressure ruptured the hose, making it necessary to abort the test. As a result of this mishap, it was decided to construct a smaller, more portable version of the injection rig to allow a closer approach to the injection point. The result of this construction is shown in Figure 14. It was essentially a specially designed variable-speed, positive displacement barrel pump, light enough to be handled by one man, yet capable of pumping a viscoelastic slurry of the consistency of chassis lubricating grease. This devise was successfully used for the preliminary injection tests, at rates up to about 4.5 pounds of polymer per minute. Full-bore capacity was about 6.0 pounds of polymer per minute.

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*The Western Company, "Polymers for Sewer Flow Control", USEPA Report No. 11020DIG08/69, August, 1969.

FIGURE 11 TRAILER-MOUNTED EQUIPMENT

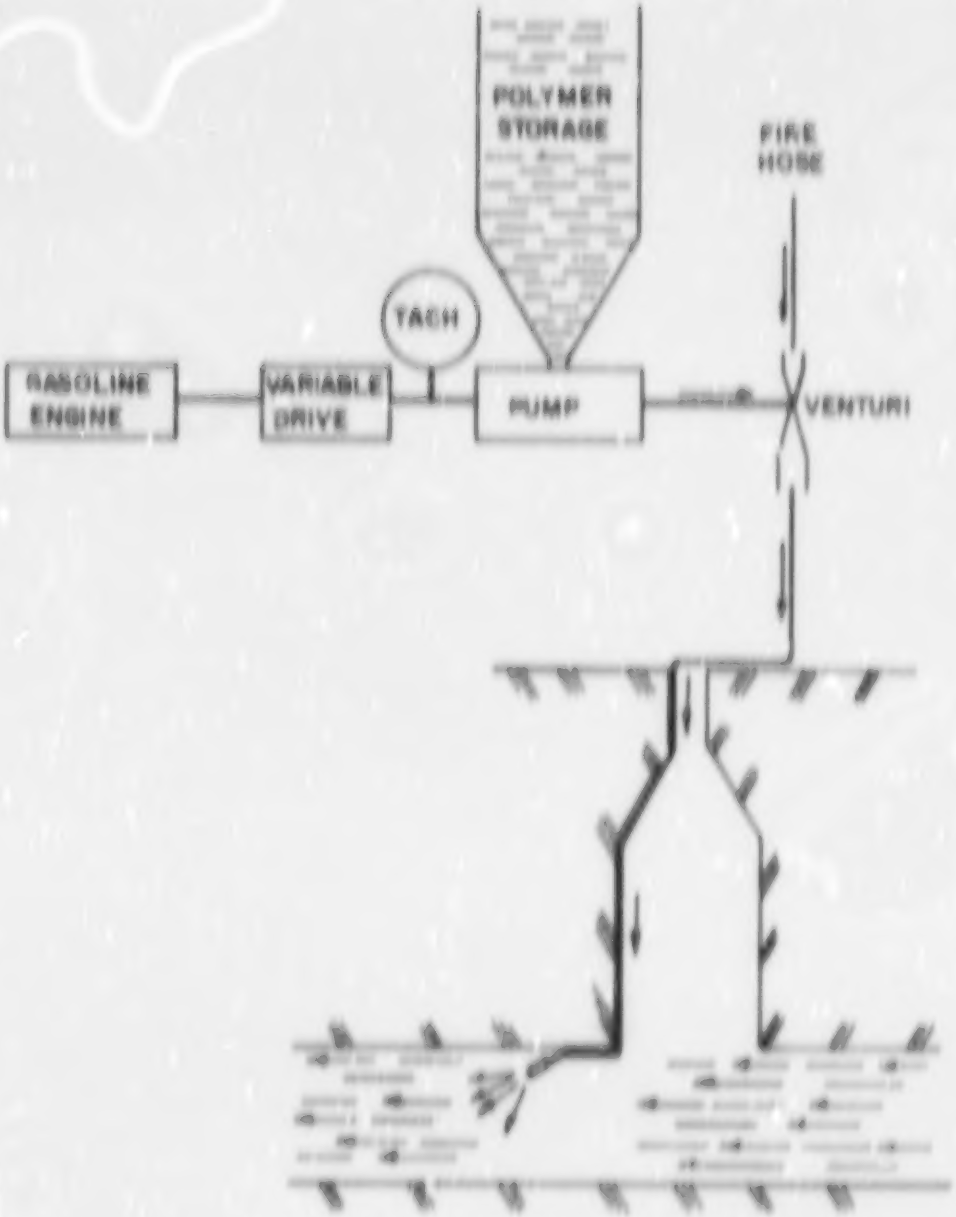
POLYMER STORAGE
FIRE HOSE
TACH
GASOLINE ENGINE
VARIABLE DRIVE
PUMP
VENTURI

Figure 12. Water-Dispersed Injection System

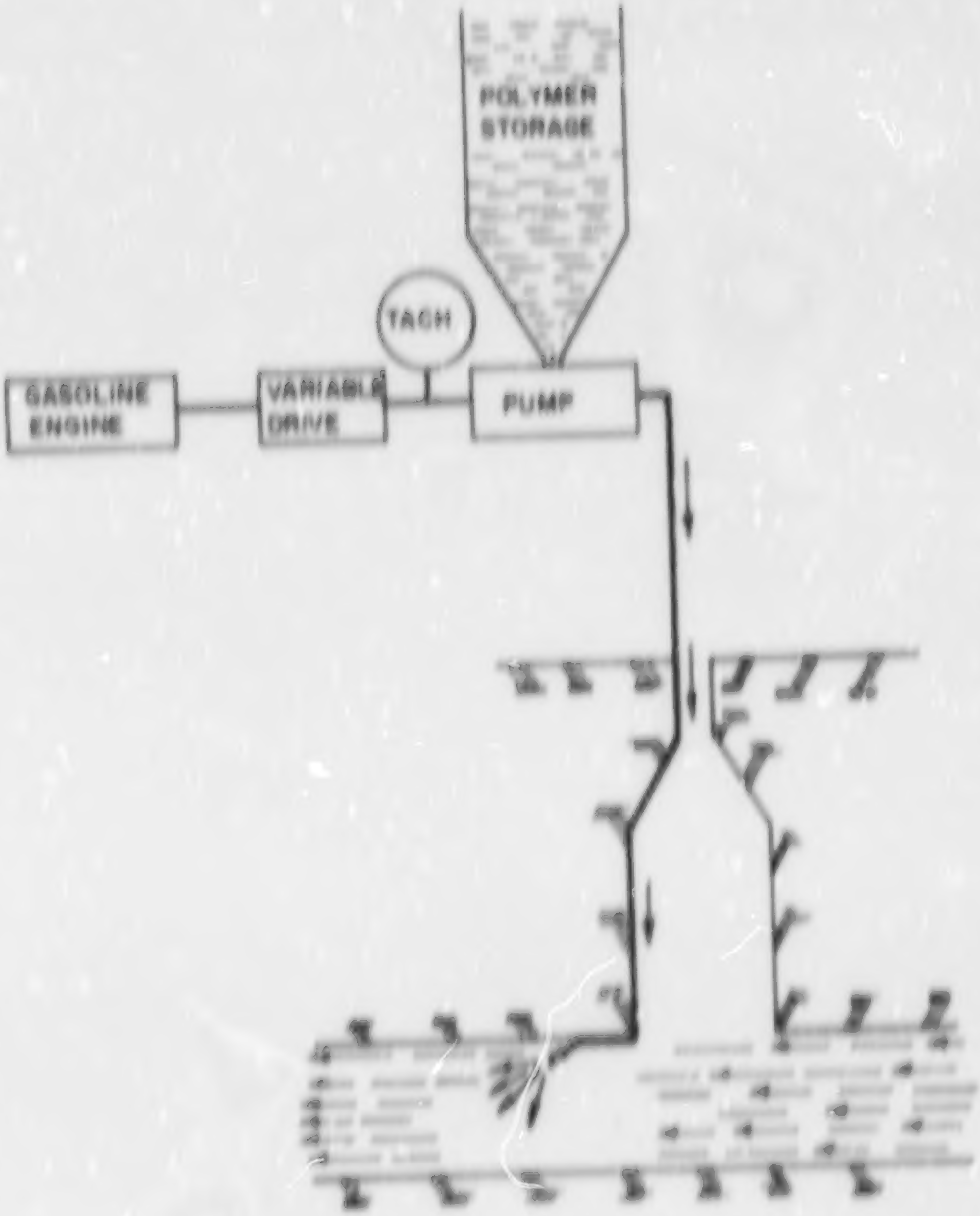
POLYMER STORAGE
TACH
GASOLINE ENGINE
VARIABLE DRIVE
PUMP

Figure 15, Modified Injection System

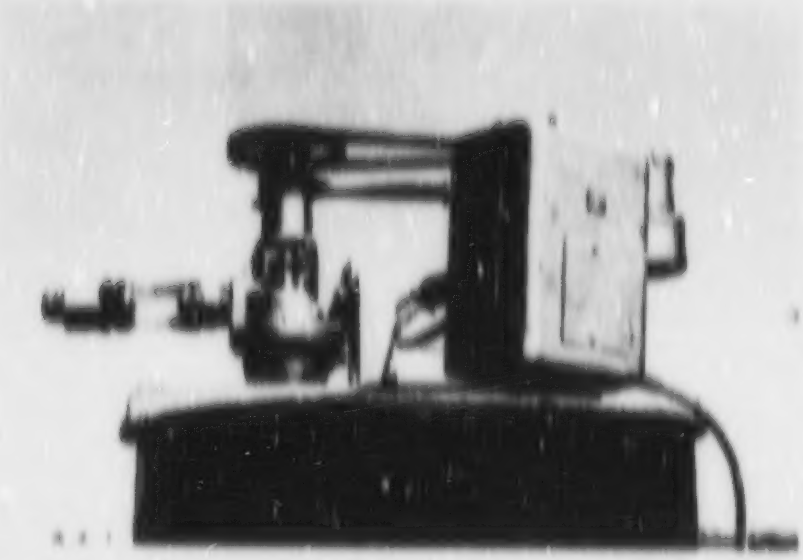

Fig. 14 Light-Weight Variable-Flow Polymer Injection Apparatus

COMPARATIVE DISPERSION TESTS OF SLURRY AND DRY FEED EQUIPMENT

Difficulties encountered in formulating and storing slurry-type polymer suspensions made it necessary to develop an alternative method for dispersing polymer solids. A primary objective of this development was a method which would allow the use of the materials in the form in which they were received from the manufacturer. Since no experimentation in sewer line friction reduction has been performed using the dry materials without the aid of a slurry or dispersing agent, it was decided to perform comparative tests with the existing slurry feed equipment and commercially available dry feed equipment.

The polymer slurry used in experimentation took advantage of the fact that a liquid in which the polymer is insoluble can serve as physical "spacer" to hold the polymer particles separated until each particle could be wetted requiring no mechanical agitation other than that present in a turbulent flow stream. In fixed plants in which polymer solutions are required, violent physical agitation replaces the non-solvent "spacer" and a solution can be made directly. A series of laboratory experiments illustrates the comparative behavior of the two systems. In these experiments, a rotary viscometer was used to determine the time required for the polymer forms to dissolve in solutions made from slurries and dry powder. The dry powder solutions were produced by introducing the required amount of material into a 1000 milliliter beaker of water violently agitated by a laboratory stirrer, while the slurry solutions were agitated by the action of the viscometer, alone. The polymer in both cases was Union Carbide Polyox WSR-301. Table 8 gives the summarized results of these tests which indicated that the dry polymer took about 50% more time for solution.

TABLE 8 RESULTS OF COMPARATIVE SOLUTION TIME TESTS OF DRY AND SLURRIED POLYOX WSR-301

CONCENTRATION (wppm)	SLURRIED POLYMER Time to 50% of Ultimate Viscosity (sec.)	SLURRIED POLYMER Ultimate Viscosity (centipoise)	DRY POLYMER Time to 50% of Ultimate Viscosity (sec.)	DRY POLYMER Ultimate Viscosity (centipoise)
1000	43	44	65	45
2000	300	55	450	60

To confirm the effectiveness of a dry feeder system, parallel tests were run using the slurry used in the experimentation and a Gaco[*] Dry Chemical Feeder. This device is installed temporarily on a 24" line in the City of Dallas which is subject to frequent surcharging. Unfortunately, the dry feeder was capable of a maximum throughput of only 0.8 pounds of dry polymer per minute, a quantity insufficient to relieve the surcharge, but adequate to produce velocity changes on the order of 10%.

The test proceeded as follows: polymer injection was started using the slurry feed. Heads and velocities were recorded continuously (head) or at 10 minute intervals (velocities). After 30 minutes of injection, the injection rate was changed. At the end of 1 hour, the slurry feeder was shut down and the dry feeder immediately started. The feed rate was changed after 30 minutes and the injection stopped at the end of the second hour. Table 9 is a summary of the results of these tests. All velocities were determined with a Gurley direct reading rotary meter.

The line in which the test was run consists of 4,127 feet of 24" diameter reinforced concrete pipe with five included manhole structures. At the velocities measured during these tests, about 14 minutes should be required for the sewage with polymer - sewage without polymer interface to travel from the injection point at the first manhole to the outfall at the fifth manhole. The data reflects this "travel time" in the amount of time required for a change in injection rate to produce a change in flow rate.

The data indicates that the dry feeder is as effective or perhaps more effective than the slurry feeder with each producing a velocity increase of about 10%. This would indicate that the times required for a polymer solution to be formed from the two polymer forms (dry and slurry) are either equivalent or the differences are not significant for field applications.

It should be noted that most polymer manufacturers recommend "aging" of the polymer solutions before use to permit adequate time for the most persistent polymer particles to dissolve. At no time during the experimental program was a solution prepared in which all the material was dissolved without "aging." The time required for aging is dependent on polymer type, particle size, solution temperature, level of agitation and concentration. From qualitative observations of these solutions it can be estimated that solutions made without aging time (as is the case in a "quick-mix" system) would actually contain only about 75 to 95 percent of the polymer being mixed.

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[*] A trademark of the Gaddis Manufacturing Company, Bartlesville, Oklahoma.

TABLE 9

RESULTS OF COMPARATIVE INJECTION TESTS OF DRY AND SLURRY FEEDERS

TIME (minutes)	INJECTION RATE (lbs/min)	CONC. (ppm)	S (ft/1000 ft)	VELOCITY fps	% CHANGE IN VELOCITY
SLURRY FEEDER:					
T = 0	0	0	4.08	4.55	0
15	0	0	4.08	4.50	-1.1
30	0.8	112	4.08	4.55	0
45	0.8	103	4.12	4.95	+8.8
60	0.8	103	4.12	4.95	+8.8
61	1.1	141	4.12	4.95	+8.8
75	1.1	143	4.08	4.90	+7.7
90	1.1	135	4.03	5.20	+14.3
DRY FEEDER:					
91	0.75	92	4.03	5.20	+14.3
105	0.75	96	4.08	4.95	+8.8
120	0.75	96	4.10	4.95	+8.8
121	0.33	42	4.10	4.95	+8.8
135	0.33	41	4.10	5.10	+12.1
150	0.33	41	4.10	5.10	+12.1
151	0	0	4.10	5.10	+12.1
165	0	0	4.12	METER FOULED	
180	0	0	4.15	4.70	+3.3

From the information gathered in the dispersion method study, a number of conclusions were formulated:

A. Dry chemical feed into an eductor-type polymer disperser is the perferred method of preparing polymer solutions.
B. There were no packaged polymer dispersing units of adequate capacity to meet the requirements of the program.
C. Since a polymer solution cannot be pre-prepared in anticipation of need, there will be some undissolved polymers introduced into the treated sewer, resulting in slight decreases in polymer efficiency.

DISPERSION EQUIPMENT FOR FIXED INSTALLATIONS.

The recommended method of dispersing dry polymer solids in water is a standard piece of equipment called an "eductor-type polymer disperser" or more simply, an "eductor." Figure 15 represents the basic construction of any eductor. It consists of a water inlet connection, a polymur inlet, and a discharge port for the mixture. Internally, it is simply a Venturi tube which generates a low pressure area which will draw air through the polymer inlet. Solid polymer materials are dispersed first in the air, and are wetted in the high energy mixing area in the lower part of the eductor. Air vents are provided to avoid wetting the upper "dry" area of the eductor in the event air flow through the polymer inlet is cut off.

Eductors of this type are available in bronze, cast iron, and stainless steel from manufacturers like Hercules Chemical Company, Penberthy, Incorporated, and Shutte and Koering. The physical configuration of eductors from various manufacturers varies but operational characteristics are similar for all units. Figure 16 shows typical eductor performance. It should be noted that the eductor requires some minimum flow to operate, and that the permissible range of feed rates is extremely broad. To utilize an eductor, it is only necessary to establish a rate of flow which will adequately disperse polymer at the maximum rate anticipated. Once this flow rate is established, any solids feed rate up to this maximum is possible without readjustment.

A type of eductor which has proved satisfactor is the "Hootenanny" manufactered by C. E. Hooten Company in Miami, Florida. This particular device is constructed of polyvinyl chloride (PVC) and Teflon which suppresses build-up of caked material on the interior surfaces. As provided from the factory, the Hootenanny has no air vents, so when mounting, a loose fit between the feed funnel and the eductor top is recommended to suporess backsplash.

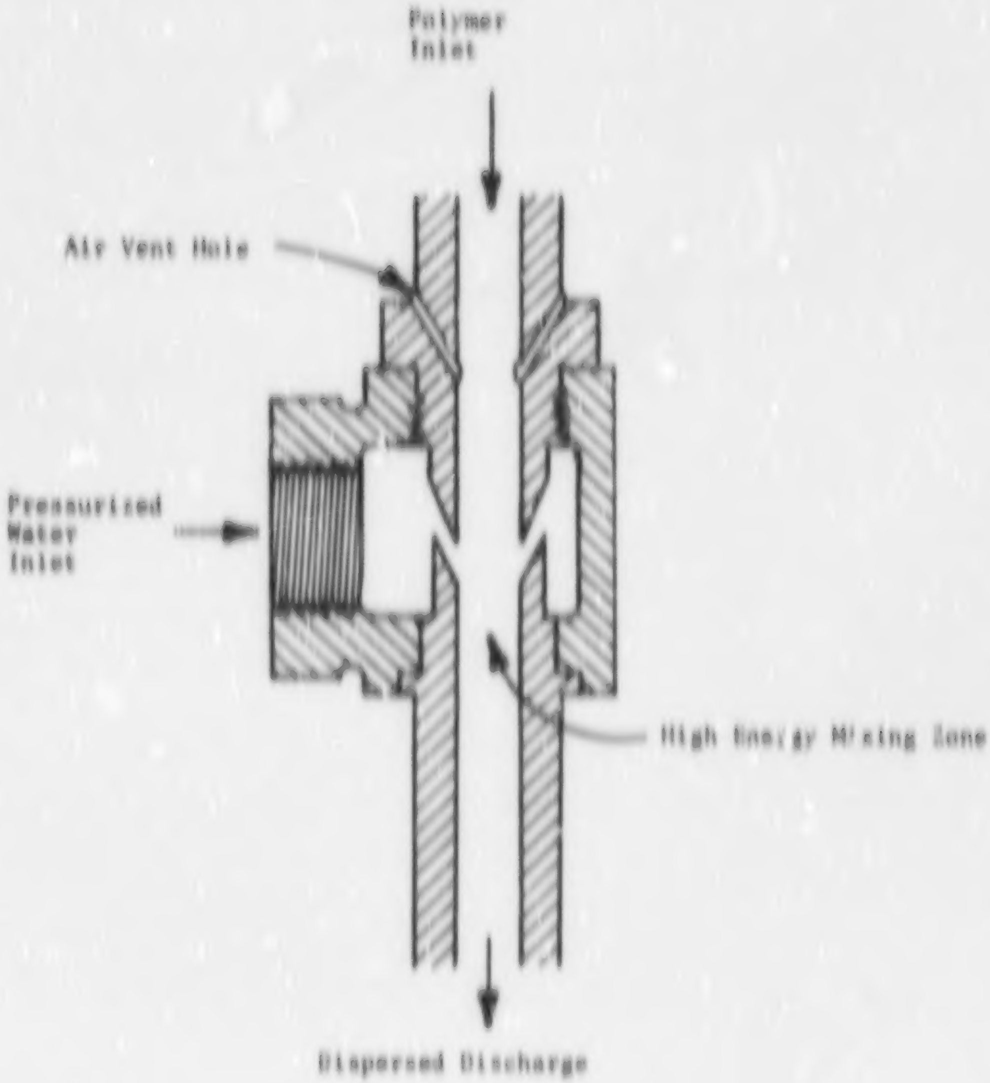

Polymer Inlet
Air Vent Hole
Pressurized Water Inlet
High Energy Mixing Zone
Dispersed Discharge

Figure 15. Typical Eductor Construction

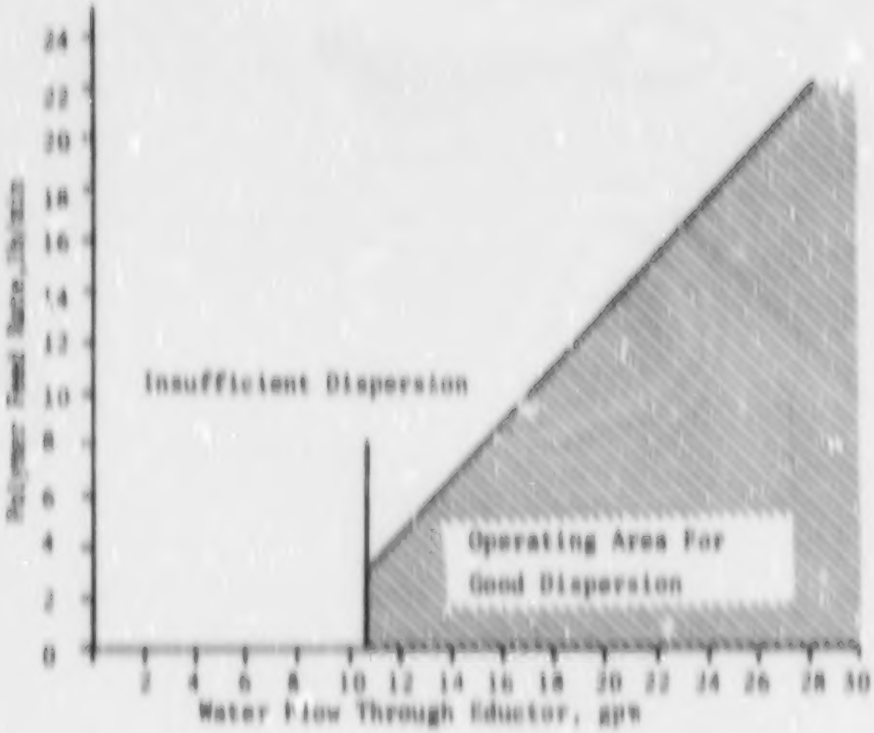


Figure 16. Operating Characteristics of
A Typical 1 1/2 Inch Disperser

FEEDERS FOR POLYMER SOLIDS

There are basically two types of feeder systems for dry polymer solids available; feed weighing systems and volumetric feeding systems. Both types of feed systems are available with a variable feed rate adjustment. The former system, which uses a weighing arrangement in a feedback loop to control the rate at which solids are fed, has the advantage that once calibrated any material may be fed at a controlled rate; that is, for a given setting of the control, all polymers will be fed at the same rate regardless of particle size and shape. However, the weighing systems are generally a great deal more complicated to maintain, and the initial cost is greater than volumetric systems.

Volumetric systems require that calibration tests be made for each material to be fed. These tests should be run over a wide range of feed rates, since the speed-feed rate relationship is not linear. Once calibration has been determined for any batch of material, the feeders can usually dispense material to within plus or minus two percent of a set rate, an accuracy which is more than sufficient for polymer injection work.

There are a number of suitable volumetric feeders available, and the manufacturers can usually provide information on the specific capabilities of their device to perform with a specific material. The requirements for specifying a suitable volumetric feeder include:

1. The feeder must be able to dose accurately and repeatably.
2. The feeder should be independent of the depth of material in the feed hopper.
3. The feed rate should be adjustable over the range of feed required.
4. The feed rate should be controllable by standard process control signal (e.g. 4-20 ma.).

A volumetric feeder which meets the above requirements and has been field tested is the Model 105-Z manufactured by Acrison, Incorporated, located in Carlstadt, New Jersey. This particular feeder has two concentric helices, one which preconditions the dry solids and the second which extrudes the material. This feeder is widely used for critical feed applications in the pharmaceutical industry.

ANCILLARY FEED EQUIPMENT

Two items of equipment which have been found virtually indispensable in a reliable solids feeding system are a polymer "clod" separator and a solids level detector. The first of these is a device to avoid feed problems and the second acts as a safety switch in the event the first fails.

Invariably, a water soluble polymer will form dry lumps or flakes when stored in stasis for long periods of time. Ball-like lumps can form from the compression caused by overlying polymer. Flakes generally form on an exposed surface or on a surface which "sweats". Many of the balls will be broken by the feed mechanism, but the flakes will generally pass through the feeder. Also, bits of foreign material may be introduced into the bulk storage tank during loading operations. Any of these items can cause a blockage in the intake of the polymer disperser and stop the polymer feed. This condition must be avoided.

Figure 17 is a design for a "clod" separator which functions adequately. The model shown was fabricated to order by a local manufacturer from plans furnished by the engineer. It consists of an inclined screen which is lightly vibrated by an external inertial vibrator. The granular solids less than one-half inch in diameter fall directly through the screen into the polymer disperser inlet, and the "clods" shaken from the surface of the screen are collected in a plastic bag.

The second piece of ancillary equipment is a capacitance solids level detector, such as that manufactured by Drexelbrook, Incorporated. The probe of this device is mounted in such a position above the vibrating screen of the polymer separator that a stoppage which produces a solids build-up in the feed funnel will react with the probe and shut down the feed. This action will prevent a messy solids spill and will make clearing of the stoppage easier. The Drexelbrook unit chosen for this function ignores film and dust build-ups on the probe, avoiding unnecessary shut-downs.

STORAGE HOPPERS FOR POLYMER MATERIALS

Polymer manufacturers recommend that the dry solids be stored in the shipping containers until used. This recommendation is based on the tendency of the polymer materials to absorb large quantities of water from the storage atmosphere, producing lumps, flakes, and in extreme cases syrupy solutions. However, if one intends to operate an un-manned, fully-automated polymer injection facility, this

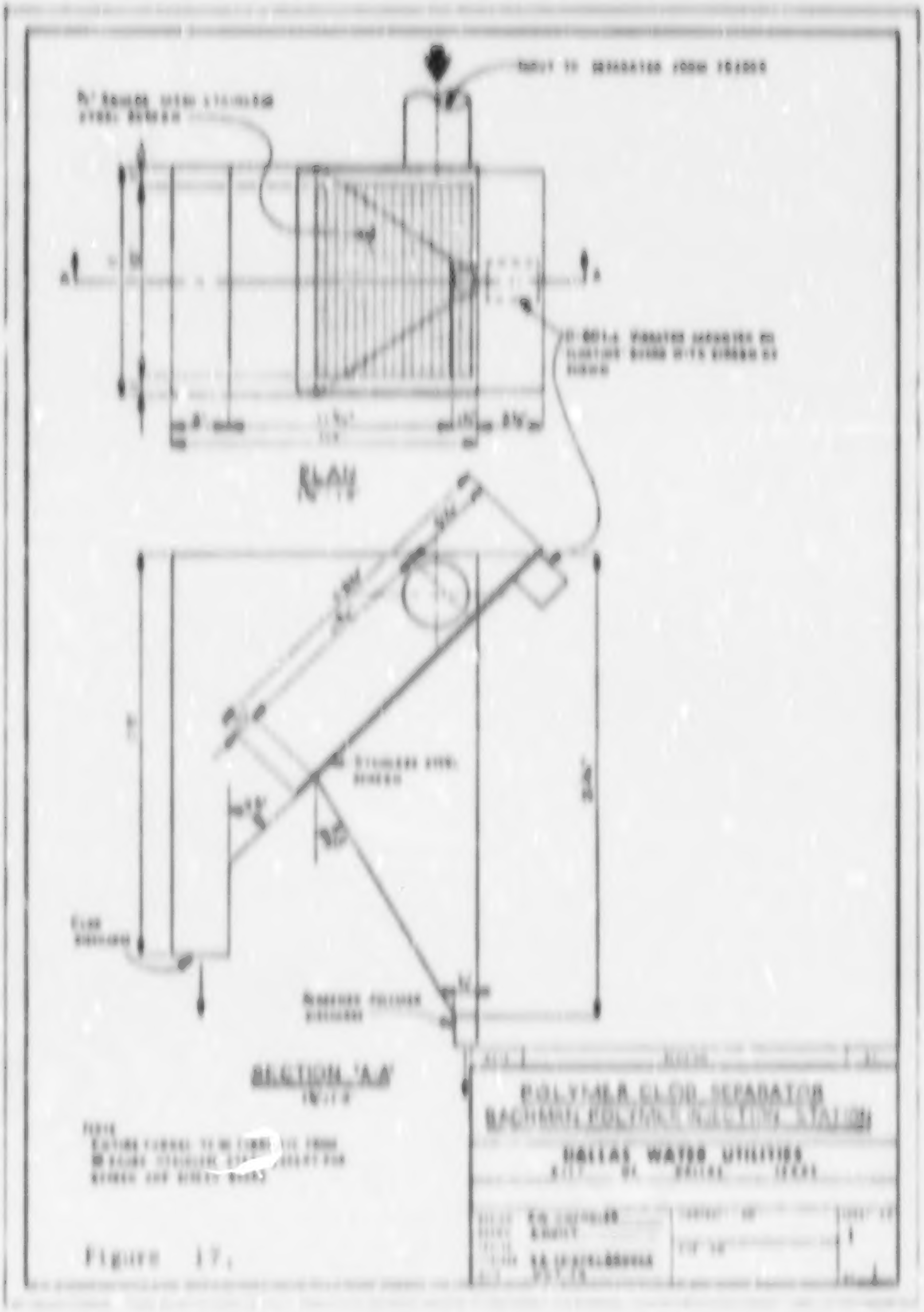

PLAN
SECTION 'A-A'
POLYMER CLOD SEPARATOR
BACHMAN POLYMER INJECTION STATION
DALLAS WATER UTILITIES
CITY OF DALLAS TEXAS

Figure 17.

implies that the polymer must be removed from its shipping container and placed in bulk storage ready for use. To insure that the materials will remain in a usable condition, this storage hopper must provide for humidity control, condensation prevention, "arch" breaking, and free feeding.

The exact dimensions and shape of a storage hopper will vary, depending on the project needs, but the basic functions will remain the same. The bottom of the storage hopper should be conical in shape, with the sides of the cone at an angle of about 30 degrees with the vertical. The angle exceeds the angle of repose of most of the polymer materials and will provide satifactory feed conditions.

After polymer materials have been stored for a long period of time, settling produces a packed structure which will bridge the discharge port. This arch must be mechanically broken either by stirring, vibration, aeration, or any combination. One satisfactory method of accomplishing this function is by using a "vibrating hopper bottom" which forms the bottom of the conical hopper and is mechanically excited. The Acrison BP Hopper Bottom is an electrically-driven product which uses a rocking motion to agitate the stored material. In general, it is convenient to use a device which is manufactured to mate directly with the feeder chosen, thereby reducing installation problems and eliminating the need for fabrication of special fittings.

If the polymer storage hopper is to be exposed to drastic temperature changes, it requires that the walls of the hopper be insulated to suppress condensation. A satisfactory method for accomplishing the insulation is by spray coating the interior surface with urethane foam, and then painting the foam with a gloss finish latex paint. The coating provides a surface to which the polymer does not readily adhere.

Dehumidification of the polymer storage area is an extremely important function, but one which is complicated by the properties of the polymers. The polymers consist of a wide grain-size distribution including some dust which will be drawn through the circulation system of a dehumidifier. This dust is then dissolved or melted in the apparatus causing air flow stoppages and overflowing drains.

There are two basic types of dehumidifiers, the desiccant type or the condensing type. The former type, such as the "Honeycombe" dehumidifier manufactured by Cargocaire Incorporated, proved to be not sufficiently rugged to resist the caustic action of the polymers, and dust drawn into the system was melted by the heat dry air, causing air flow restriction. Therefore it is recommended that a condensing type of dehumidifier be utilized.

Those portions of the dehumidifier that will come in contact with the polymer dust should be of materials which will resist caustic action. For example, aluminum coils, enclosures, and ducting should be avoided unless the surface is coated or plated with a more inert material.

INJECTION OF DISPERSED POLYMERS

After the polymer has been fed through a disperser and mixed with water, the resulting mixture gets to a viscous state very quickly as more and more of the solids go into solution. If the feeding and dispersing apparatus were to be mounted directly over a sewer line so that the dispersion could discharge freely into the sewage, the problem of injection would be non-existant. However, in many cases the dispersion will be performed at some distance from the sewer line and the dispersion piped to the desired injection point.

The design of the eductor-type disperser prohibits the attachment of long discharge piping directly. The common method of overcoming this is to allow the discharge of the disperser to fall into a "buffer" tank, and then pump the dispersion to the injection location. The size of the pump and the volume of the tank should be such that the dispersion is not allowed to "age" more than about one minute, the permissible aging time being determined by the solution characteristics of the polymer used.

Referring to Figure 16, it can be noted that it is possible to disperse approximately 8 pounds of polymer in as little as 16 gallons of water. This corresponds to a solution concentration of about 6 percent. At this concentration, the polymer solution (fully dissolved, or aged) has an estimated viscosity in excess of 100,000 centipoise. In other words, the solution could be formed into balls and bounced. Therefore, the time which the dispersion resides in the buffer tank is very critical. Even before the solution is fully aged, the material can become so viscous that the injected material will resemble a rope and fail to disperse in the sewage as is required in order to be effective.

The buffer tank should be made of a non-corrosive, smooth-finish material such as stainless steel, polyethylene, or polypropylene to withstand the caustic reaction of the polymer solution and to facilitate wash down.

A centrifugal pump will not suffice to pump the viscous dispersion of polymer and water. A positive displacement pump capable of passing the undissolved, dispersed solids should be used. A progressive cavity pump such as a Moyno screw pump with stainless impeller and neoprene stator is satisfactory, but sometimes inconvenient in geometry. A gear pump with cast iron case and bronze impellers such as those manufactured by Worthington perform satisfactorily, although some corrosion of the pump case will be encountered. When sizing the pump and drive motor a viscosity of 2000 centipoise should be considered as the minimum.

If the dispersion is handled rapidly, no special provision for injection into the sewer line are necessary. A satisfactory method consists of attaching the injection piping flush with the inside wall of the sewer with the discharge at right angles to the flow in the sewer. The turbulence in the sewer line will complete the dispersion process.

If, for some reason the polymer dispersion tends to reach the extrudable state before reaching the sewer line, the amount of water used in the initial dispersion must be increased, or, additional water can be added to the buffer tank. Supplemental mixing energy may be required if the latter option is chosen.

SECTION 7

PROCESS CONTROL AND INSTRUMENTATION FOR POLYMER INJECTION

RELATIONSHIP BETWEEN INSTRUMENTATION AND PROCESS CONTROL

Although it is physcially possible to inject a friction-reducing material into a sewer line and qualitatively observe the results (many experiments have been so performed), it would not be possible to efficiently dose the material, control the process, or even evaluate the effectiveness of the technology. The starting time of an injection will usually be determined by a rising head in the sewer, but the rate at which the polymer is to be injected is most efficiently determined by proportioning to the flow rate. These two operational aspects require the installation of static pressure gauges at critical locations on the line and at least one flowmeter at some point on the line. Hence, the equipment required for process control is also the minimum instrumentation signals required to evaluate the effectiveness of injection.

REQUIRED PROCESS CONTROL INSTRUMENTATION

Process contrul instrumentation is required in two separate functional areas: (1) external to the injection facility to provide "real world" data; and (2) inside the station to control the injection process. The external equipment is as discussed above. The internal equipment performs the following functions:

1. Polymer Feeder Rate Control
2. Injection Pump Start-Stop Control
3. Polymer Agitator Start-Stop Control
4. Process Overflow Shut-Down
5. Process Failure Shut-Down
6. Injection Completion Clean-Up Control
7. Injection Start-Up Sequencing

The need for each of these functions will be discussed individually, since some installations may not require every function. To start an injection process correctly, a number of things should happen in the following sequence:

a. Mixing water flow to the eductor should be established.
b. The polymer storage hopper should be agitated.
c. The polymer "clod" separator vibrator should be activated.
d. The polymer feeder should be started.
e. The polymer dispersion injection pump should be started.

If the feeder starts much in advance of the agitator, arches may form above the moving hopper bottom, requiring some other action to restart the solids flow. If the solids feeder is started before the water flow through the eductor is established, the solids will clog the polymer inlet. In a similar manner simultaneous cessation of solids feed and water flow at the end of the injection period will leave solids in the feed train which can cause clogging during the next feed interval.

A control scheme which will execute the required functions is illustrated in Figure 18. Beginning at the left of the diagram a "run" signal which can be derived from a set point relay which responds to head at critical points on the sewer opens a solenoid valve, allowing water to enter the process. The water pressure then activates a pressure switch which turns on the bin agitator and clod separator, and begins a time "on" delay for the polymer feeder. At the end of the pre-set delay the feeder starts at a rate determined by the flow through the sewage flowmeter, and a dispersion is discharged into the buffer tank. A low level switch starts the injection pump. During an injection a solids build-up in the clod separator will stop the solids feed until the stoppage is cleared manually. In a like manner, a pump failure will activate a high level sensor in the buffer tank, causing the solenoid valve to close. The absence of water pressure will immediately stop the solids feeder, killing the process until the problem is corrected.

In normal operation, the disappearance of the "run" signal starts the timing cycle of a time delay "off" relay which will hold the solenoid valve open, but will shut down the solids feed. This action provides a clean water flush of the dispersion and injection systems, leaving the process ready to perform at the next "run" signal.

SELECTION OF PROCESS CONTROL COMPONENTS

The first step in selecting process control components, once the control scheme is selected, is to decide on the primary signal amplitude which will be utilized in the system. Standard signals include 1 to 5, 4 to 20, and 10 to 50

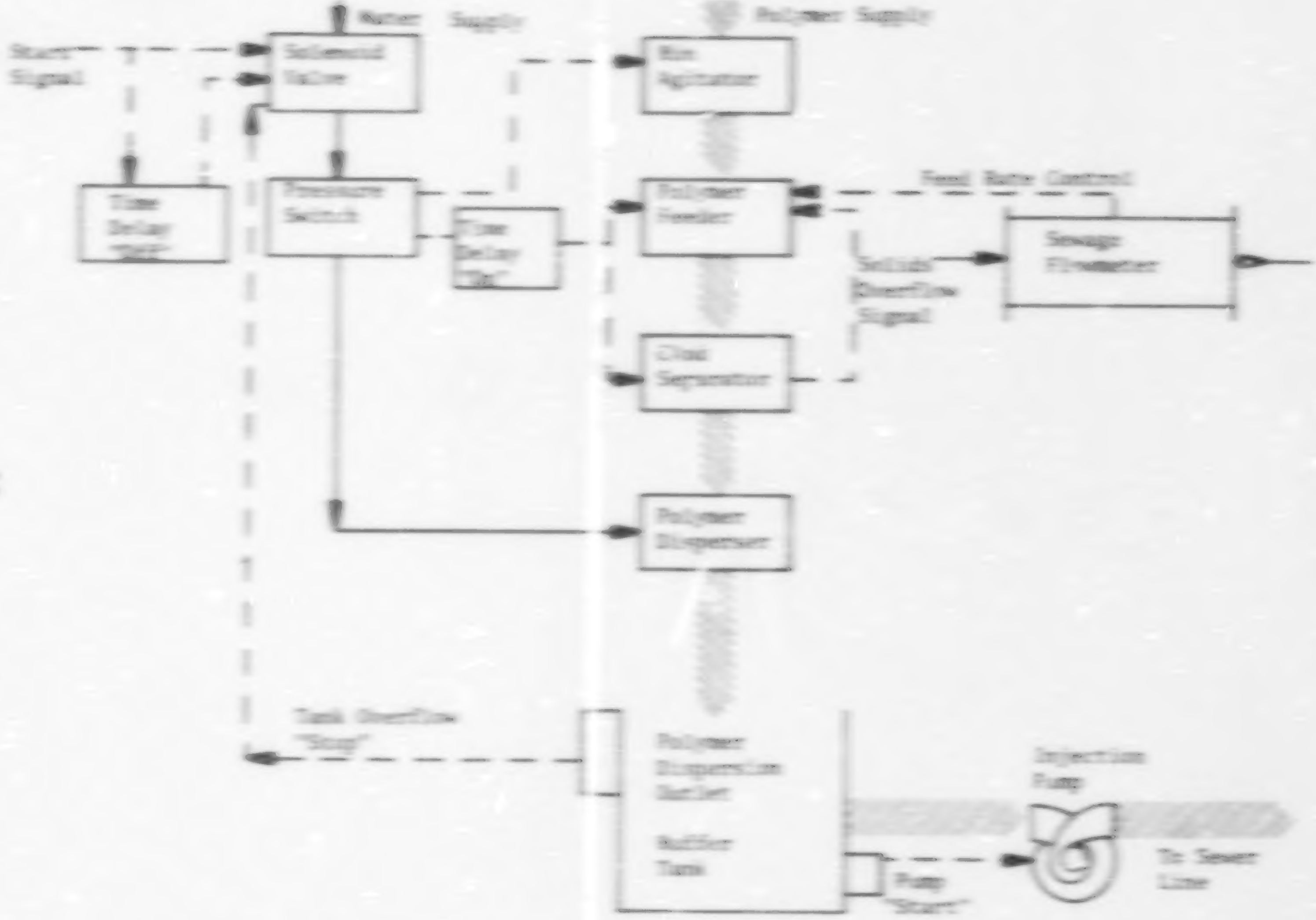

Start Signal
Water Supply
Solenoid Valve
Time Delay "Off"
Pressure Switch
Time Delay "On"
Polymer Supply
Mix Agitator
Polymer Feeder
Feed Rate Control
Sewage Flowmeter
Solids Overflow Signal
Clod Separator
Polymer Dispenser
Tank Overflow "Stop"
Polymer Dispersion Outlet
Buffer Tank
Pump "Start"
Injection Pump
To Sewer Line

Figure 16. Suggested Process Control Scheme for Polymer Injection

milliamperes direct current, and 1 to 5 volts direct current. The 4 to 20 milliampere DC signal is one of the most commonly used, and there are many manufacturers who can provide control elements and indicating devices for this signal range. Which range is chosen is not important, but it is important that the signals be compatible throughout.

A secondary signal for the direct operation of motor starters, solenoid valves and operation equipment can be either a low voltage DC or AC line current. The latter is convenient, but greater care must be taken in the layout of equipment to minimize shock hazards to maintenance personnel.

A few guidelines which should be considered during the selection and assembly of process control equipment are as follows:

1. The control system and the elements which comprise the system should be as simple as possible.

2. Reliability of components should be stressed, with particular attention to the state in which a failure will leave a control.

3. All relays used in the system should be of the enclosed type.

4. All connecting wiring should be color-coded or marked at frequent intervals with easily readable wire markers. Terminations on terminal strips should be clearly marked with unique identifiers.

One piece of equipment which deserves special mention is the sewage flowmeter. A meter should be chosen which does not restrict flow in the line, and which will respond correctly to non-Newtonian flows. This last restriction eliminates the possibility of using Venturi tubes, orifice plates, and flow nozzles. Two types of metering which are satisfactory are electromagnetic velocity sensing and ultrasonic velocity sensing. Satisfactory devices of the first type are manufactured by Fischer and Porter, Brooks Instruments, and others. This type of meter should be ordered with a Neoprene or polyurethane liner. Ultrasonic electrode cleaners are not recommended. The second type of meter is manufactured by Nusonics, Inc., Sparling Meter Co., and others; and can be built into a section of almost any type of pipe. Installation of the latter device must include provisions for flushing across the transducer faces with clean water.

SECTION 8

PRECAUTIONS IN STORING AND HANDLING POLYMER

PROTECTION OF POLYMER MATERIALS

Shipping containers of polymer materials are either polyethylene-lined fiber drums or polyethylene-lined multilayer bags. These containers should be stored in a covered area and kept sealed until transferred into an environmentally-controlled bulk storage container. The containers should not be stored in close proximity to steam or hot water pipes, heaters or other hot surfaces. Exposure to direct sunlight should also be avoided because the resins are thermoplastic with a low melting point.

SAFETY PRECAUTIONS

The polyethylene oxides are formed by the reaction of a gaseous monomer and as a result the presence of unreacted monomer is not a problem. As previously mentioned, the polymer gives a basic reaction (solution pH = 10) so the dust can cause minor irritation of mucous membranes and of the sensitive eye parts. Allergic reaction is possible as with any material. Polyethylene oxides are non-toxic and can be ingested without causing difficulties. The large molecule is relatively undigestable and will pass through the system essentially unmodified. The FDA has recognized and approved the use of Polyox in certain food uses including packaging as well as a direct additive to malt drinks (beer, ale) up to a proportion of 300 parts per million.

The Environmetal Protection Agency has approved Polyox for unrestricted use as an inert ingredient in pesticide formulations under Regulation Number 180.1001.

The polyacrylamides may contain small quantities of unreacted monomers which are toxic until hydrolyzed by mixing with water. They have a tendency to be more irritating than the polyethylene oxides and dust masks and goggles are recommended.

When the polymers are handled in a closed system, the possibility exists that the concentration of dust could build up to such a degree that a dust explosion could occur. This fact should be considered in designing handling systems such as bulk storage bins and pneumatic conveyers.

Containers in which polymers have been stored should never be used for strong oxidizing agents such as potassium permanganate ("potash"), sodium hypochlorite (HTH, Chlorox), or hydrogen peroxide. The polymer molecule is a long, active hydrocarbon chain which can provide a concentrated fuel source. A mixture of Polyox and HTH, when wetted with water, will often burst into flame. Unauthorized use or disposal of the polymer materials by persons unaware of the potential danger should be avoided.

SECTION 9

EVALUATION OF A SYSTEM FOR POTENTIAL USE OF FRICTION REDUCING AGENTS

POSSIBLE APPLICATIONS OF FRICTION REDUCERS

The operator of a wastewater collection system should consider friction reduction as an alternative to other methods of relief, such as pumping, based on a thorough engineering investigation of the basic problem, including evaluation of economic considerations. This section of the report presents a recommended sequence of steps in that investigation and evaluation.

It is probably safe to say that all operators of sanitary sewage collection systems have faced, or will face, the problem of gravity mains which are under-capacity because of unpredicted population growth patterns, changes in land utilization after the system has been built, or most often, because they are overloaded by water from infiltration and inflow sources. In most cases, the permanent solution to overloaded sewers can be found by re-engineering, re-building or rehabilitating the offending sewers. However, occasions will arise which will require a problem solution on an interim basis until a permanent solution can be effected. It is in these cases that the application of water-soluble polymers as friction reducers may be most useful.

In those cases when sewers overload and surcharge infrequently, such as during major storms, it may not be economically feasible to reconstruct a part of the wastewater collection system. In these situations, it is possible that permanent polymer injection points may be a suitable alternative. As in other projects, the decision to use this particular technology must be based on the probability that the desired results can be achieved, the initial investment required, and the on-going operation and maintenance costs associated with the constructed facility.

EVALUATION OF A COLLECTION SYSTEM SEGMENT

The first step in the engineering of a possible friction-reduction application should be an analysis of that part of the collection system in which surcharges are evident. This step in the evaluation should be performed regardless of the action contemplated.

The evaluation should begin with a determination of the frequency and approximate duration of the surcharging, and more importantly, the frequency and duration of the resulting overflows. A rough estimate of the flow rate in the sewer will suffice to make a first estimate of the cost of polymer injection. A concentration of 50 parts per million may be assumed as a normal value and the annual cost of polymer injection calculated as follows:

Polymer Cost = Flow Rate (gpm) x 8.33 pounds/gal
x (50×10^{-6}) x Duration of Overflow (min)
x Annual Number of Overflows x $1.25/pound

If the polymer cost derived above is within reason, then the evaluation can be continued with a thorough definition of the flow-head loss characteristics of the system. Studies to determine flow rates should be performed in the most accurate manner possible, and apparent anomalies should be carefully investigated to insure that observed head losses are actually due to friction losses. There have been a number of cases reported in which obstructions, offset joints, sloppy manholes, or other loss-producing elements were the causes of overflows. All such head-loss producers should be corrected if possible, before the data necessary to produce head-discharge curves is gathered.

Concurrent with the effort to gather the above data, construction drawings should be reviewed to determine "critical" elevations in the flow network. These "critical" elevations are the points in the system at which the hydraulic grade line first reaches an elevation sufficient to produce overflows. Care must be taken to consider that overflows may occur through branch lines and building service connections. Since the elevations of these types of potential overflows may not be shown on system construction prints, field surveys and the establishment of level nets may be necessary.

When the critical elevations for the flow network have been determined, these points may be plotted on a profile sheet. The line connecting the points plotted in this way will establish the upper limits of the hydraulic grade line which cannot be exceeded without causing overflows. A comparison should then be made between the grade line so constructed and a hydraulic grade line based on the values for flow and friction factor measured during the field studies. This second line should be constructed as if standpipes were to be placed at every overflow location, thereby eliminating the overflows. Candidate injection locations can be determined by inspection of the differences between the actual hydraulic grade line and the required hydraulic grade line.

The second check for the feasibility of friction reduction can now be made by calculating the required friction-reduction efficiency using Equation (17) and the existing and required friction factors. As discussed in Section 4, the maximum possible efficiency is 80 percent, and the practical maximum will be on the order of 60 percent. If the calculation performed indicates feasibility, the next step in the analysis is justified.

Since the limiting value of the hydraulic grade line has already been established, the next operation is to calculate the shear stress which the head loss characteristic of the grade line represents. This is done by utilizing Equation (9). Once the shear stress is determined, the value for various materials at several concentrations may be determined using Equation (22) and the appropriate constants previously determined by experiment. These ϕ values determine corresponding values of $R(\phi)$ (Figure 8), which can then be used to determine achievable friction factors. If it is possible to produce a friction factor sufficiently small, it has then been determined that friction reduction will result in head reductions or in flow increases.

RELATIONSHIP BETWEEN HEAD REDUCTIONS AND FLOW INCREASES

It has been pointed out in a preceding section that friction reduction can result in either head reductions or flow increases, or a combination of both phenomena. If one is interested in stopping overflows, head reduction is usually required, but is not always achievable even with high efficiency friction reduction. There is no quick approach to determine if head reductions will result from reduced friction losses. A definitive analysis of the piping system upstream of the point of polymer application is necessary. The need for this analysis is illustrated in the following discussion.

Downstream of an injection location, the effective friction factor will be reduced. Using the Darcy-Weisbach equation for frictional head loss, if the velocity (flow rate) through the pipe with a reduced friction factor were to remain constant, there would be a reduction in head loss proportional to the reduction in friction factor. However, the flow in the pipe immediately upstream of the injection point is also affected since we have now reduced the head at the downstream end of that pipe. The effect of this head reduction is to increase the amount of sewage delivered to the injection point, thereby increasing the head at the injection point. To further complicate matters, it should be noted that the effect of the injected polymer on the friction factor can also be affected by the change in flow conditions, requiring a recalculation of the friction factor. The sketches of Figure 19 are intended to aid in the clarification of this concept.

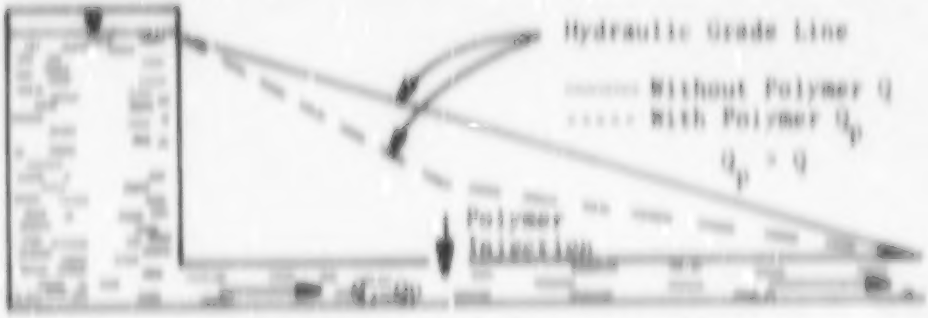

Hydraulic Grade Line
Without Polymer Q
With Polymer Q_p
$Q_p > Q$
Polymer Injection
Q_p

Figure 19(a). Polymer Injection To Change Head and Flow

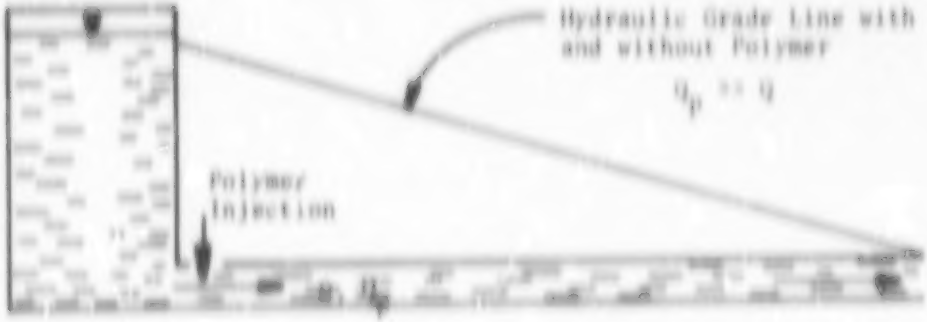

Hydraulic Grade Line with and without Polymer
$Q_p >> Q$
Polymer Injection
Q_p

Figure 19(b). Polymer Injection To Change Flow Only

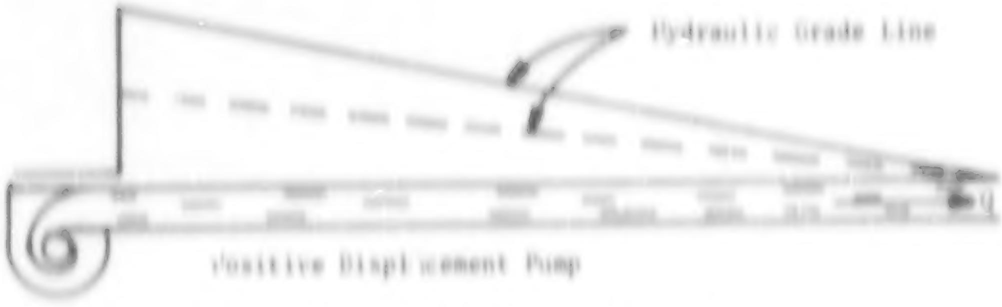

Hydraulic Grade Line
Q
Positive Displacement Pump

Figure 19(c). Polymer Injection To Change Head Only

The analysis of the flow system to determine the effect of friction reduction will consist of the following steps:

1. For the material, concentration, and flow conditions anticipated, determine the modified friction factor of the sewer line downstream of the injection point.

2. Calculate the expected head at the injection point by summing the head losses downstream of the injection point.

3. Using the head calculated in Step 2, calculate the increased flow in the upstream network. To be complete, the calculation should be performed for every pipe to the limits of the flow network.

4. Use the new flow found in Step 3 to recalculate friction factor.

5. Repeat Steps 2 through 4 a sufficient number of times that the change in the calculated flows become negligible.

Upon completion of the analysis just described it may be found that the head reduction which will be produced will be adequate to eliminate overflows, or it may be found that polymer injection will result in flow increases only. In the event that the calculations indicate the latter situation, the feasibility of polymer injection for overflow relief is weakened, but there is one additional possibility which may be considered.

The feasibility analysis discussed in the preceding section was based on the premise that the collection system network was filled, heads sufficient to produce overflow were existing, and that head reductions were required "after-the-fact" to stop the overflows. The second possibility would be to evacuate the excess water in the system at a rate sufficient to prevent the system from becoming overly full by starting injection earlier in the period of maximum input, thereby making space in the system to accommodate the excess water at the peak input rate.

When an infiltration/inflow analysis is performed on a collection system segment, one of the requirements is to differentiate between infiltration and inflow. In a graph of flow versus time for a gravity sewer line, an inflow event is usually characterized by a very rapid increase which begins soon after the beginning of a storm, and whose duration is related to the duration of precipitation. This type of flow increase produces rapid surcharging and overflows, and the peak rate of excess flow will generally exceed the capabilities of the friction reduction technology. However, if these sources of rapid input can be eliminated, the excess flows of infiltration which generally increase more slowly and endure longer, can be accommodated by an earlier injection start. This technique would obviously also apply to any input which causes a slow rise in system flows.

SECTION 10

RELATIONSHIP BETWEEN RAINFALL AND SEWER OVERFLOWS

During the performance of the preliminary tests, rainfall data was collected from all of the Water Department gauging stations around the city. Four of the stations were selected as representative of the drainage area, stations numbers 27, 41, 43, and the official United States Weather Bureau Love Field Station. The location of those stations in relation to the trunk line is shown by the circled numbers in Figure 20A.

Tables 10 and 11 are a listing of the 1969 and 1970 rainfall records of the selected stations and an arithmetical average of the four stations for each day that any precipitation was recorded at one or more stations. The "T" found in the table indicates rainfalls of less than 0.01 inch. Data reflects rainfall for the 24 hours preceding the date on which the data was recorded. For instance the rainfall recorded for January 1, 1970 occurred between 0800, December 31, 1969 and 0800 January 1, 1970.

Figures 21 and 22 are bar graphs of the average rainfall recorded in Tables 10 and 11. The star symbols mark those periods of time when overflows occurred in the drainage system. Unfortunately, the exact periods of overflow during 1969 were not on record, but the rainfall data is presented for comparison.

Some anomalies can be noted on the bar chart. For instance, although a rainfall which averaged 0.97 inches over the test area produced overflows on March 20, 1970, a rainfall of 1.44 inches on March 17, 1970 did not cause overflows.

The problem of relating rainfall to flow in a sanitary sewer is not equivalent to relating rainfall to flow in combined or storm sewer. In the case of a storm or combined sewer, a unit hydrograph is constructed using the measured drainage area, rainfall intensity and a coefficient for runoff dependent on terrain and ground cover. Infiltration, on the other hand, is dependent not only on those variables listed above but on the type of soil and the history of rainfall and temperature for some period of time preceding the overflow. A qualitative example of this is the comparison of the lags between rainfall and overflow start for two similar rains, May 31 and September 2. The overflow of May 31 started approximately six hours after the rainfall began, but the lag on September 2 was only three hours.

A possible explanation lies in the difference of condition of the ground at the two periods. The soil is largely a plastic clay over weathered limestone. In the spring, the clay is swollen and forms a relatively impermeable surface. On the other hand, by September the ground is dry and cracked to considerable depth. This same shrinkage can cause severe problems if a shallow line, such as a house lateral, is not properly installed. The shrinkage cracks provide a ready passage of water to the limestone, which is relatively permeable.

A simple regression analysis was performed using the limited data available. The results of the analysis led to the following conclusions:

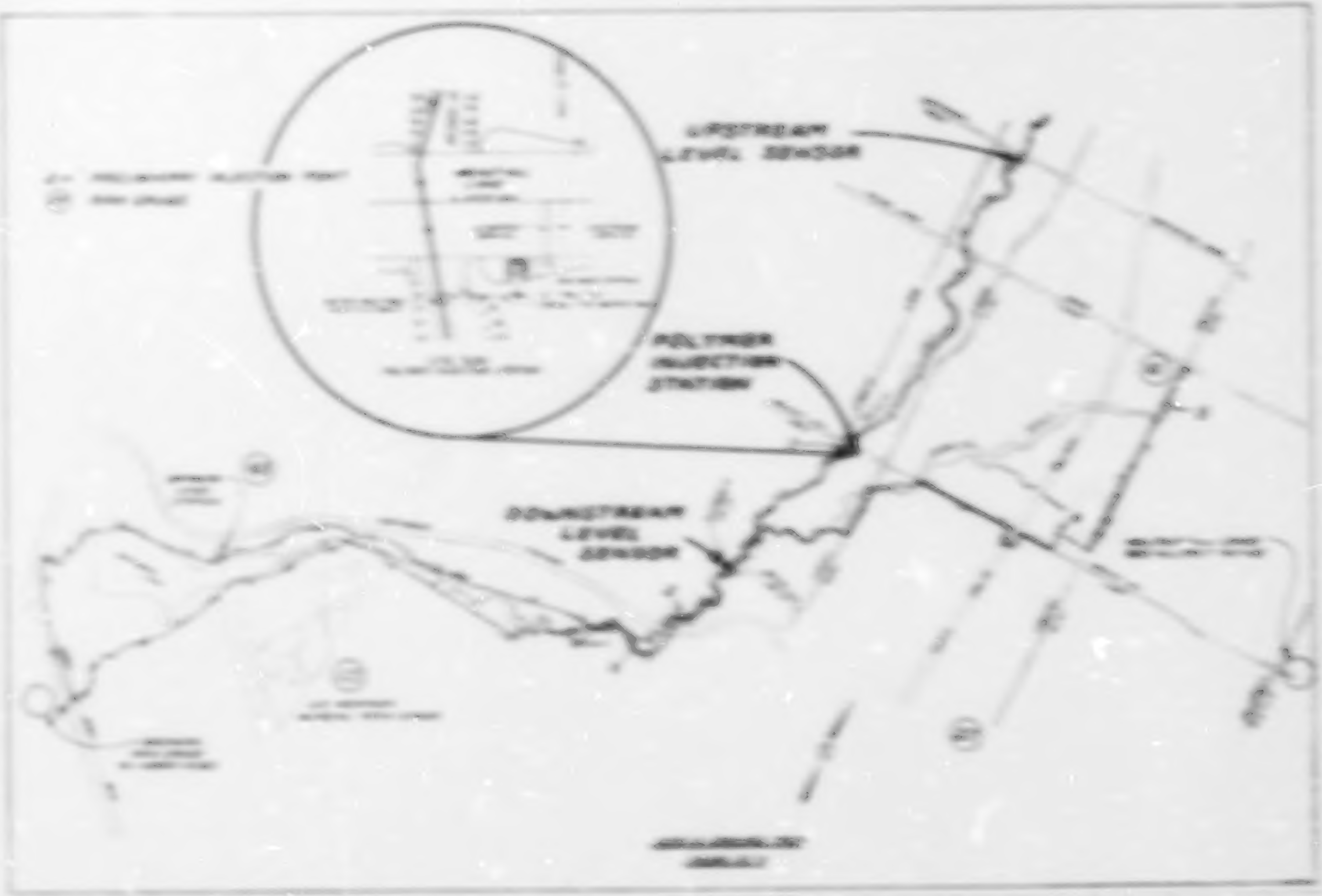
A. A total rainfall of at least 3.5 - 4.0 inches in any 20 day period will cause overflows.

B. A total rainfall of at least 4.5 - 5.0 inches in any 30 day period will cause overflows.

Further analyses will be possible as additional data is gathered.

For future work, another rain gauging station has been installed in the northwest section of the drainage area. It is anticipated that a more rational relationship between rainfall and overflow can be developed with additional data over the life of the project.

Table 12 relates the volume and duration of overflow with the dates on which rainfall covered such overflows. It can be seen that the period during which overflows persisted for the various storms ranged from 9 to 39 hours. It should also be noted that the overflow "patterns", although similar, were not the same for every flooding condition.


UPSTREAM LEVEL SENSOR
POLYMER INJECTION STATION
DOWNSTREAM LEVEL SENSOR

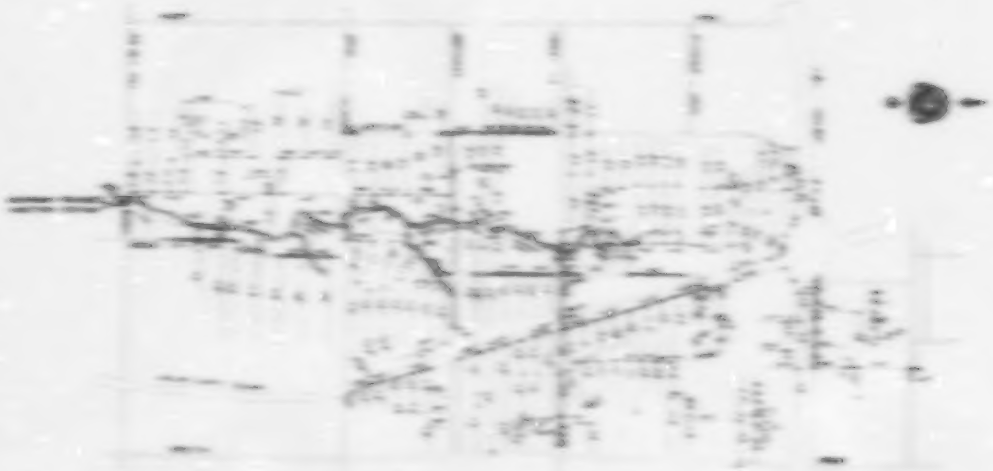


FIGURE 20-8

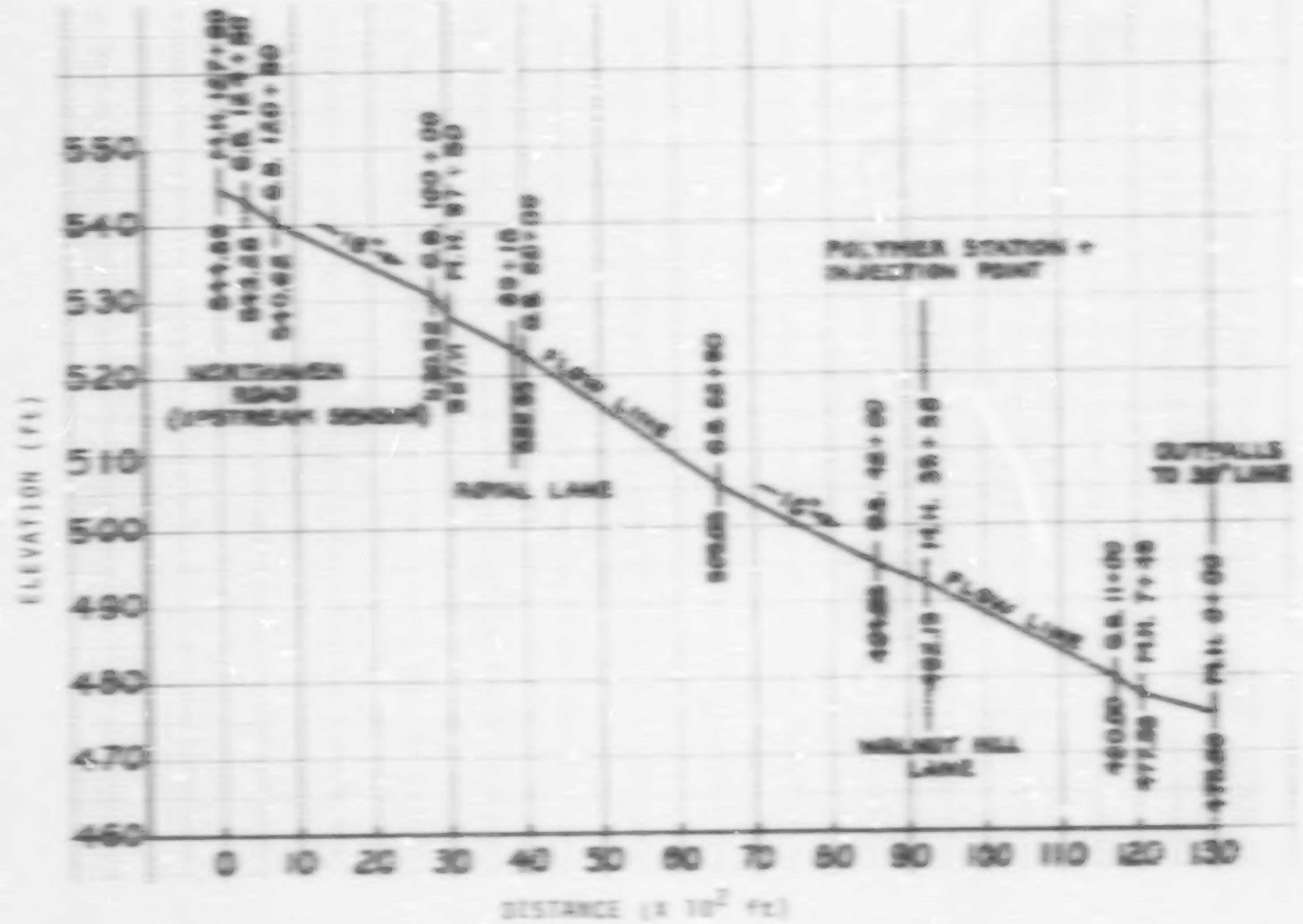


FIGURE 20-C PROFILE BACHMAN CREEK 18" LINE

TABLE 10. 1969 RAINFALL RECORD (Values in inches)

Month	Day	Station Number			Weather Bureau	Average
		27	41	43		
January	16	0,05	0,10	0,13	0,04	0,08
	29	0,10	0,14	0,1	0,1	0,85
	30	2,39	1,70	0,86	1,90	1,71
February	1	0,07	0,10	0,14	0,09	0,10
	14	0,3	0,33	0,36	0,32	0,26
	15	1,12	1,00	0,94	0,96	1,01
	20	0,3	0,13	0,14	0,09	0,10
	21	0,46	0,50	0,43	0,49	0,47
	22	0,45	0,44	0,52	0,34	0,44
March	3	0,45	0,51	0,44	0,40	0,45
	6	0,30	0,29	0,34	0,32	0,31
	8	0,34	0,20	0,19	0,22	0,24
	15	1,00	1,01	0,80	0,55	0,84
	16	0,85	1,02	0,84	0,67	0,85
	18	0,77	0,80	0,79	0,68	0,76
	23	0,69	0,70	0,75	0,35	0,62
	24	0,10	0,10	0,12	0,39	0,18
	25	0,02	0,17	0,0	0,02	0,05
	31	0,33	0,20	0,32	0,14	0,24
April	5	0,10	0,06	0,15	0,15	0,11
	13	1,15	1,15	1,05	0,92	1,07
	16	0,0	0,0	0,65	0,0	0,16
	17	0,60	0,60	0,0	0,40	0,40
	27	1,19	0,86	1,38	1,14	1,14
May	5	2,38	1,98	2,26	2,05	2,17
	7	4,50	4,50	5,60	4,96	4,89
	8	0,35	0,86	1,10	0,46	0,69
	9	0,06	0,03	0,22	0,02	0,08
	15	0,59	0,50	0,52	0,25	0,47
	17	0,49	0,65	0,73	0,66	0,63
	18	0,40	0,50	0,63	0,44	0,49
	26	0,0	0,02	0,32	0,04	0,10
	27	0,76	0,78	0,09	0,04	0,42
	29	0,60	0,15	0,08	0,09	0,23
June	1	0,0	0,04	0,06	0,02	0,03
	4	0,25	0,27	0,30	0,28	0,28
	24	0,09	0,10	0,11	0,10	0,10

TABLE 10 (continued) 1969 RAINFALL RECORD

Month	Day	Station Number			Weather Bureau	Average
		37	41	43		
July	-	0,0	0,0	0,0	0,0	0,0
August	5	1,05	0,68	1,75	1,67	1,29
	10	0,20	0,26	0,44	0,59	0,37
	24	0,27	0,25	0,0	0,09	0,15
	26	0,45	0,15	0,74	0,0	0,33
September	3	0,78	0,40	0,92	0,98	0,77
	4	0,57	0,60	0,65	0,39	0,55
	8	0,20	0,33	0,0	0,08	0,15
	9	0,45	0,20	0,25	0,0	0,23
	11	0,12	0,19	0,13	0,0	0,11
	17	0,18	0,0	1,05	0,0	0,31
	19	0,0	0,33	0,0	0,0	0,08
	23	1,35	1,68	2,10	1,71	1,71
October	5	0,11	0,04	0,08	0,03	0,06
	12	2,30	2,25	0,96	2,26	1,94
	13	2,00	2,30	2,66	2,13	2,27
	28	0,58	0,63	0,75	0,73	0,67
	29	0,86	0,22	0,26	0,28	0,40
	30	1,71	2,17	1,83	1,87	1,90
November	3	0,05	0,15	0,12	0,11	0,11
	4	0,52	0,41	0,56	0,43	0,48
	17	0,66	0,47	0,95	0,57	0,66
	27	0,27	0,20	0,22	0,20	0,22
December	6	0,98	1,02	1,25	0,81	1,02
	7	0,51	0,50	0,59	0,50	0,53
	28	0,04	0,10	0,09	0,11	0,09
	29	1,28	1,60	1,55	1,63	1,52
	30	0,07	0,10	0,17	0,14	0,12

TABLE 11 1970 RAINFALL RECORD (Values in Inches)

Month	Day	Station Number			Weather Bureau	Average
		47	31	33		
January	2	0.22	0.14	0.05	0.15	0.14
	5	0.12	0.12	0.11	0.14	0.18
	6	0.40	0.42	0.34	0.36	0.38
February	1	1.33	1.50	1.31	1.12	1.32
	3	0.25	0.11	0.0	0.28	0.16
	6	0.04	0.06	0.04	0.03	0.04
	7	0.48	0.52	0.55	0.48	0.51
	8	0.01	0.08	0.0	0.02	0.02
	15	0.65	0.55	0.45	0.39	0.51
	16	0.02	0.01	0.20	0.19	0.11
	23	0.28	0.40	0.35	0.22	0.31
	24	1.05	0.75	0.63	0.60	0.77
	25	1.04	1.10	1.35	1.05	1.13
	28	0.85	0.75	0.76	0.68	0.76
March	2	0.02	0.01	0.0	0.02	0.02
	3	0.60	0.85	1.25	0.75	0.86
	7	0.18	0.21	0.20	0.14	0.18
	11	0.40	0.45	0.43	0.38	0.41
	12	0.20	0.16	0.25	0.14	0.19
	17	1.48	1.10	1.85	1.32	1.44
	19	0.08	0.06	0.05	0.03	0.05
	21	0.95	0.92	1.14	0.87	0.97
April	10	0.10	0.14	0.15	0.10	0.12
	16	0.34	0.45	0.35	0.31	0.36
	17	0.90	0.39	0.12	0.13	0.36
	19	0.95	0.80	0.61	0.81	0.68
	25	0.87	0.68	0.92	0.81	0.83
	26	1.12	1.50	1.80	1.24	1.46
	29	1.00	0.0	0.0	0.0	0.25
	30	0.0	0.0	0.36	0.21	0.28
	31	0.0	0.0	0.0	0.31	0.08
May	1	0.41	0.45	0.43	0.31	0.40
	23	0.05	0.0	0.03	0.12	0.05
	27	0.45	0.44	1.00	0.12	0.50
	28	0.95	0.57	0.93	0.68	0.78
	30	0.22	0.72	0.65	0.19	0.44
	31	2.05	1.50	3.09	1.76	2.15

TABLE 11 (continued) 1970 RAINFALL RECORD

Month	Day	Station Number			Weather Bureau	Average
		27	31	33		
June	1	0.0	0.07	0.20	0.0	0.06
	5	0.0	0.0	0.02	0.0	T
	21	0.0	0.0	0.23	0.19	0.10
	23	0.42	0.0	0.45	0.48	0.34
July	11	0.0	0.0	0.0	0.01	T
	12	0.0	0.0	0.11	0.05	0.04
	13	0.0	0.25	0.27	0.25	0.19
	21	0.02	0.0	0.0	0.0	T
	25	0.0	0.0	0.06	0.20	0.06
August	19	0.0	0.0	0.0	0.95	0.24
	20	3.02	1.90	2.68	1.09	2.17
	23	1.98	1.90	1.74	1.61	1.81
	30	0.0	0.01	0.69	0.73	0.36
September	1	0.70	0.50	0.64	0.55	0.60
	2	3.56	3.20	1.95	2.15	2.71
	3	0.45	0.0	0.0	0.08	0.13
	14	0.33	0.45	0.70	0.72	0.55
	17	0.0	1.30	1.76	0.72	0.94
	18	0.0	0.04	0.05	0.0	0.02
	21	0.0	0.0	0.0	0.03	T
	22	0.0	0.0	0.17	0.28	0.11
	23	1.10	1.30	1.96	1.95	1.58
	26	0.60	0.50	0.68	0.65	0.61
	27	0.03	0.0	0.0	0.01	T
October	6	0.16	0.0	0.02	0.07	0.06
	8	0.0	0.0	0.0	0.03	T
	9	0.0	1.00	0.24	0.34	0.39
	12	1.52	1.33	1.27	1.60	1.43
	18	0.0	0.03	0.02	0.01	T
	24	1.11	1.05	1.15	0.94	1.06
	26	0.0	0.05	0.0	0.0	T
	27	0.0	0.0	0.0	0.02	T
November	14	0.51	0.40	0.35	0.32	0.40
December	16	0.0	0.0	0.17	0.20	0.10
	21	0.05	0.30	0.04	0.0	0.10
	30	0.77	0.72	0.82	0.73	0.76

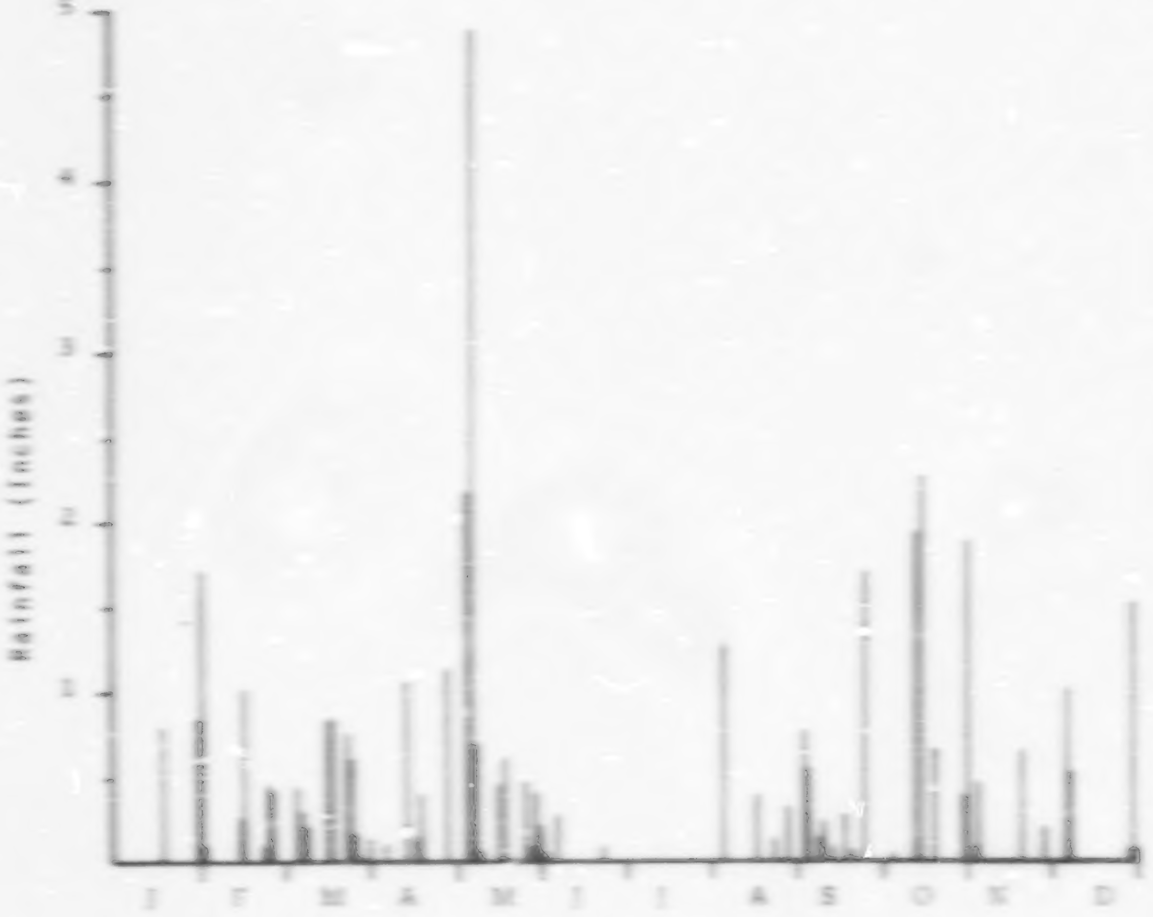


Figure 21. Rainfall Record - Bachman Watershed (January - December 1969)
Data from Four Stations

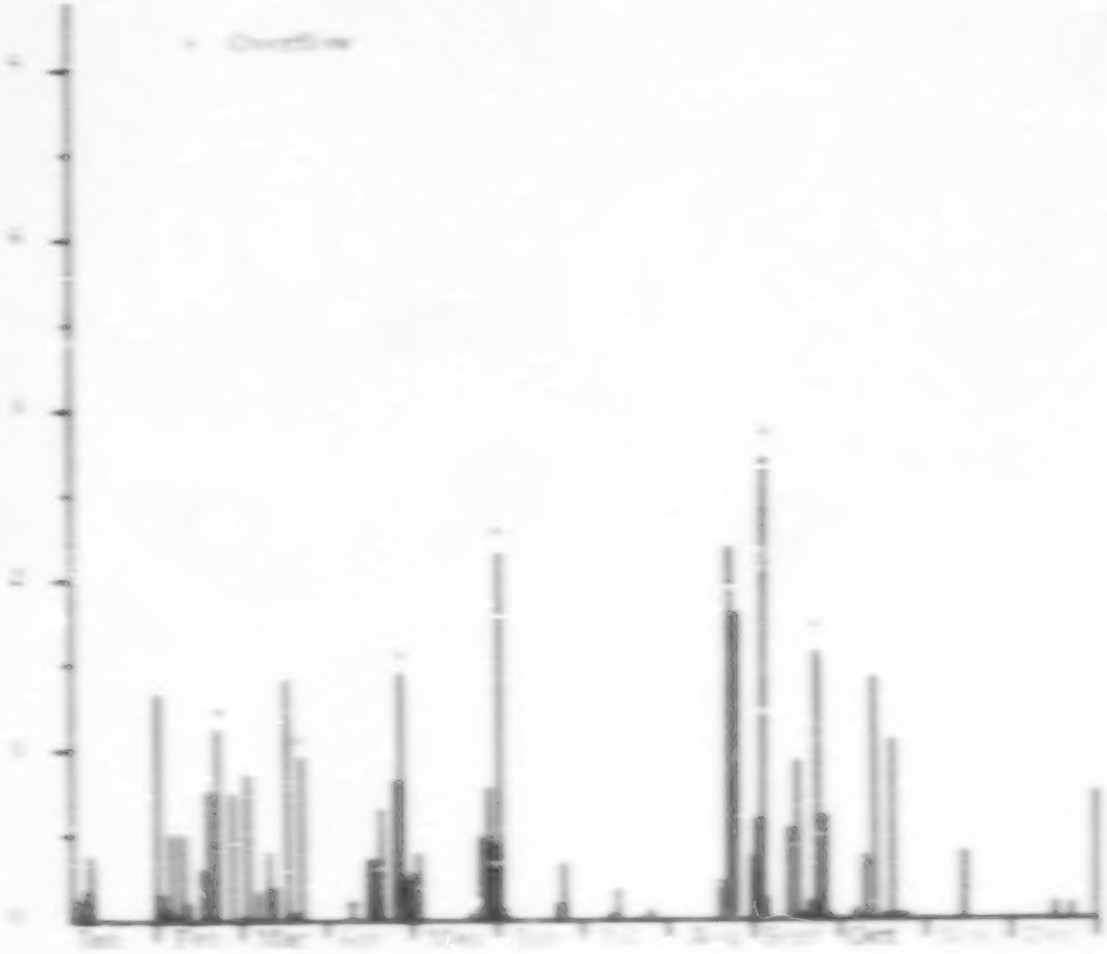


Figure 22. Rainfall Record - [illegible] Watershed (January - December [illegible])
Data from Four Stations

TABLE 11.
OBSERVED OVERFLOWS IN THE BACHMAN CREEK WATERSHED
DURING CALENDAR YEAR 1970

Showing $\frac{\text{Peak Rate Observed (gpm)}}{\text{Duration (hrs)}}$ (See Title)

Overflow Number																
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
#	—	#	#	#	—	#	—	#	#	—	—	—	—	—	—	—
$\frac{200}{6}$	$\frac{20}{19}$	#	R	#	$\frac{0}{0}$	$\frac{0}{0}$	$\frac{0}{0}$	R	$\frac{500}{16}$	$\frac{300}{19}$	#	#	#	#	#	#
$\frac{400}{6}$	$\frac{10}{30}$	$\frac{0}{0}$	R	$\frac{0}{0}$	$\frac{0}{0}$	$\frac{0}{0}$	#	R	$\frac{600}{15}$	$\frac{\#}{16}$	#	#	#	#	$\frac{250}{19}$	#
$\frac{75}{5}$	$\frac{\#}{\#}$	$\frac{0}{0}$	R	$\frac{0}{0}$	$\frac{0}{0}$	$\frac{0}{0}$	$\frac{0}{0}$	R	$\frac{100}{32}$	R	#	#	#	#	$\frac{175}{22}$	R
$\frac{\#}{\#}$	$\frac{0}{0}$	$\frac{0}{0}$	R	$\frac{0}{0}$	$\frac{0}{0}$	$\frac{0}{0}$	$\frac{0}{0}$	R	$\frac{100}{4}$	R	#	#	#	#	$\frac{50}{4}$	R
$\frac{50}{4}$	$\frac{0}{0}$	$\frac{0}{0}$	R	$\frac{0}{0}$	$\frac{0}{0}$	$\frac{0}{0}$	$\frac{0}{0}$	R	$\frac{1000}{6}$	R	$\frac{200}{\#}$	$\frac{200}{\#}$	$\frac{200}{\#}$	$\frac{200}{\#}$	$\frac{250}{14}$	R

The symbol # indicates the occurrence of an event with no quantitative record.
R indicates overflow removed or closed.

The above table is a chronological list of activity at observed overflow points. The activities listed are for the following days in calendar year 1970, respectively: Feb. 25, March 21, April 25, May 30, September 2 and September 23.

SECTION II

HYDRAULIC LINE ANALYSIS AND COMPUTER MODELING

GENERAL

Technical literature presents a number of ways by which the relationship between flow, conduit properties and energy loss can be expressed. In most cases, these expressions differ only by the empirically-derived constants supplied to make the mathematical formula and the physical model consistent.

Normal application of flow equations by engineers is through the use of nomographs and tables, with occasional spot calculations to check the results obtained. Analysis of the flow system of this project was accomplished through the use of nomographs, tables, and direct calculation, but in addition, electronic processing was used to permit more analysis, with an eye toward the solution of a general "Branched-network" flow problem.

The basic equation chosen for use in analysis and modeling is the Hazen-Williams Formula* expressed in the form:

$$v=C_1\ r^{0.63}s^{0.54}\ 0.001^{-0.04} \qquad (24)$$

v= average velocity in feet per second
C_1= a coefficient of "roughness"
r= a/p=hydraulic radius, feet
s= energy loss per foot of pipe.

This equation can be transformed into the familiar "power law" equation for round pipes by making the following substitutions:

$Q= 1/4\ \pi D^2 x\ v x\ 448.86$
$D/4= R$ (round pipes flowing full)
$\Delta h/L=s$

where:

Q= flow, in gallons per minute
D= pipe diameter in feet
Δh= head loss due to friction in feet of water
L= length of pipe

---

* "Handbook of Hydraulics", 4th Edition, 1954, McGraw-Hill.

The resulting equation is: $$\Delta h = \frac{[9.76 \times 10^{-5} L]\, Q^{1.85}}{C^{1.85} D^{4.865}} \qquad (25)$$

The quantity enclosed in the bracket is a constant assigned the name "K" for a given length of pipe; therefore, the friction loss in a length of pipe is proportional to the flow in the pipe raised to a "power", hence, a "power-law" equation.

It should be kept always in mind that dilute polymer solutions do not obey this equation, since the equation was based on experimental data for water, a Newtonian fluid. Therefore, the computer model discussed in the following is only applicable to a system before polymer addition is made. The complex problem of calculating the effect of polymer addition in flowing systems is discussed in Section 4 of this report.

The values of C_1 used in the analysis are shown below:

Pipe & Condition	C_1
Extremely smooth, straight	140
Very smooth	130
Vitrified	110
Concrete	100
Tuberculated concrete	80
Small, rough concrete	60

Once a method of calculation was chosen, it was necessary to make assumptions concerning quantities of sewage normally input into the line and the infiltration conditions which produce overflows.

Table 13, "Land Use Parameters Used in Model", was extracted from WPCF Manual of Practice 9, "Design and Construction of Sanitary and Storm Sewers" (1969). The average flows given in this table are representative of the average design flows used by the City of Dallas. For ease in programming, no variation with tributary area was considered. The demographic data concerning average-to-peak flow ratios shown in Figure 1 were also extracted from the above reference and corresponds with the criteria established for the Dallas systems.

COMPUTER MODELING

The purpose of modeling is to accurately simulate, in as many ways as possible, the behavior of a physical system under any perturbation desired, or required. The model developed under this program is a mathematical representation of a "branched-network" flow problem. A branched network differs from a closed network (as represented by a water distribution system)

TABLE 13 LAND USE PARAMETERS USED IN MODEL

Land Use	Average Density (residential uses in persons per acre)	Average Flow (Q)	
		Gallons/Day/Acre	Mgd Sq. Mile
Rural or Conservation	2.5	250	0.160
Institutional	-	500	0.320
Low Density Residential	5.5	550	0.352
Medium Density Residential	9.5	950	0.608
Commercial	-	1500	0.960
Medium-High Density Residential	16	1600	1.024
High Density Residential	25	2500	1.600
Industrial	-	4000	2.560

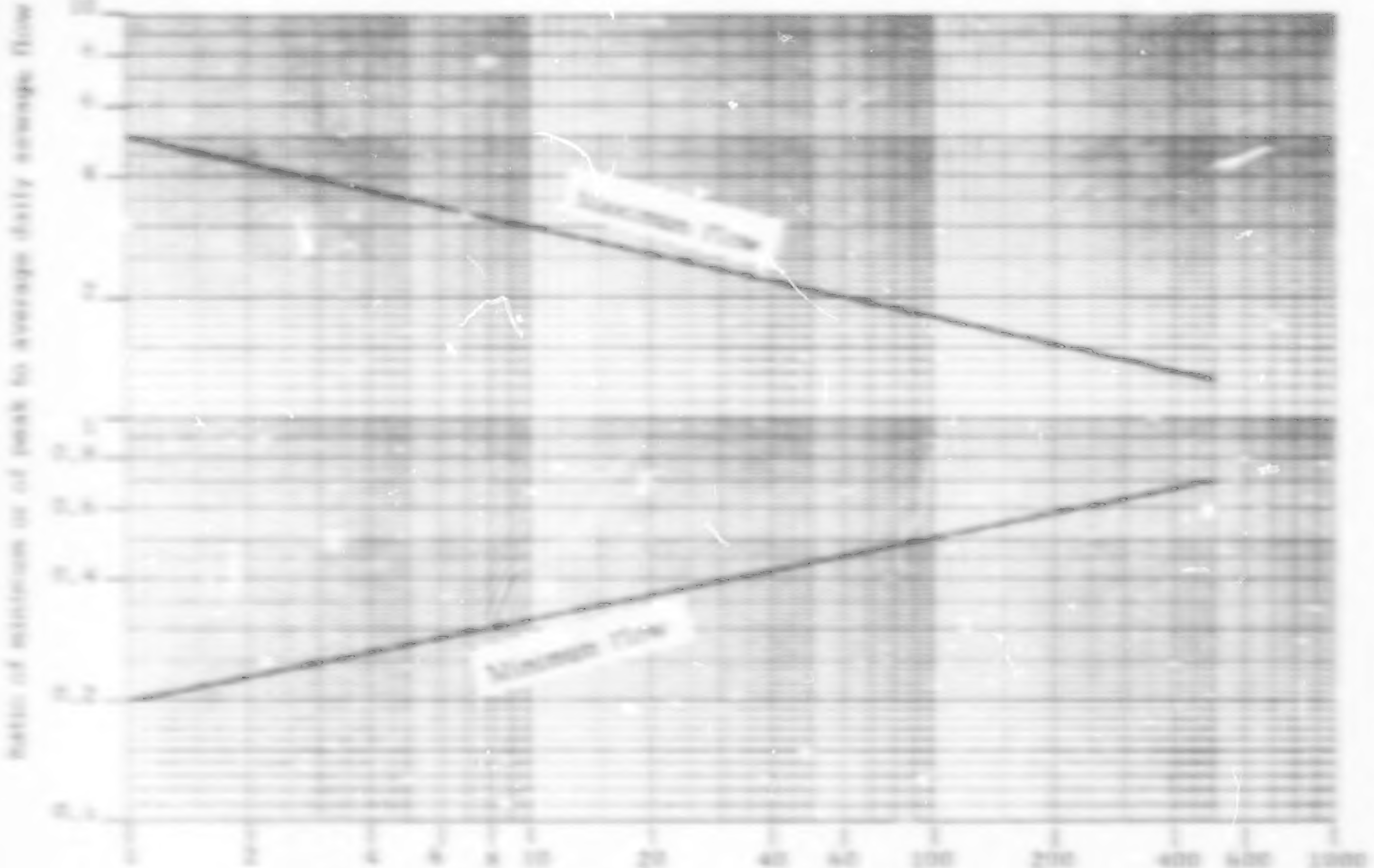


Figure 22 Ratio of Peak to Average Sewer Flows Versus Population (Based on National Averages)

in the increased number of restraints and conditions as input data. The model also differs from that used for design* in that the operator does not have the freedom of generating pipe sizes, slopes and geometry.

The computer program presented here is designed as an 'on-line' Fortran program, requiring the attendance of a person knowledgeable of the purpose and method of the program to furnish additional data or to change input parameters. The program was prepared and run using the GE time-sharing computer service. The following discussion is presented as an example and user's guide.

INDEXING CONVENTION

The flow network is first broken into 'lines' as shown in Figure 24 with the index '1' being assigned to the most downstream line. The lines are then numbered, in order, by assigning even numbers to the deadend branch lines and odd numbers to those lines which are joined to other lines at their upstream end.

The next step in subdivision is to assign numbers to each node or 'entry' along the previously defined line, starting at the most downstream end with '1' and proceeding upstream. An 'entry' is required for each input from a lateral line, each change in pipe size or characteristic (e. g., roughness), and for junctions with other 'lines'. It should be noted that laterals or lateral lines are distinct from 'lines'.

The last index is that 'serial', which is either '1' or '2'. The serial differentiates between two laterals entering at the same entry. In the analysis of the Bachman Trunk Sewer, a '1' indicates a lateral entering from the north or west and a '2' indicates a lateral entering from east or south.

GEOMETRIC RESTRICTIONS

Constructed overflows are treated as special cases of lateral lines.

The program is designed to accept a sewer network consisting of one trunk line fed by 'n' dead-end branch lines as illustrated in Figure 24. The number of branches ('n') is limited only by the capacity of the computer used to process the problem. A branch line may not be split into sub branches.

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* Zepp, Paul L., 'A Computer Program for Sewer Design and Cost Estimation', Regional Planning Council, 701 St. Paul Street, Baltimore, Maryland
21202 (April 1969).

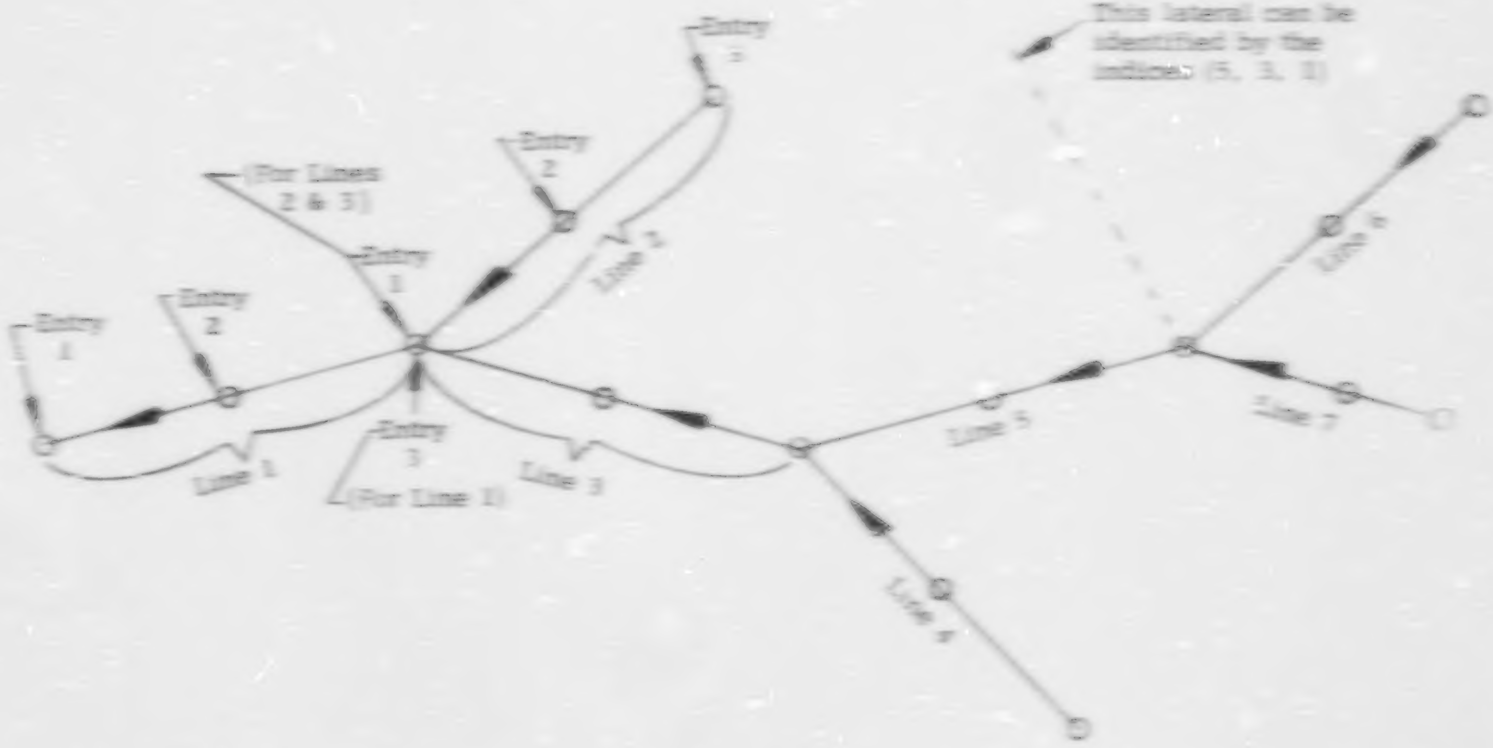
Entry
1
Entry
2
(For Lines
2 & 3)
Entry
1
Entry
2
Entry
3
Entry
3
(For Line 1)
Line 1
Line 2
Line 3
Line 4
Line 5
Line 6
Line 7
This lateral can be
identified by the
indices (5, 3, 1)

Figure 24. Example Flow Network Showing Indexing Convention

To simplify processing, no more than two laterals may feed any numbered entry. If more than two inputs are desired, two or more adjacently numbered entries may be defined to be connected by pipes of length 1×10^{-6} feet.

INPUT DATA REQUIREMENTS

Input is accomplished by entering data into permanent "files" (time-sharing systems) or "tapes" (batch systems). The required data is defined in groups in the order required for processing.

The first data input describes the geometry of the system to be analyzed. It consists of the number of lines, and then for each line: (1) the line number; (2) the number of entries on the line; and (3) a "0" if the line dead-ends or a "1" if the line is joined by other lines at its extreme.

The second data input describes the tributary areas along the lines in the system. For each lateral or constructed overflow along each of the lines the following data is required:

A. The line, entry, and serial identifying the lateral (Or overflow).

B. The area of the tributary area in acres.

C. The land use factor in gallons/day/acre as shown in Table 13.

D. The critical, limiting or overflow elevation on the lateral or overflow.

E. The estimated or measured total collector pipe length in the tributary area.

F. The design roughness (C in Hazen-Williams Formula) of the connected lateral.

G. The diameter and length of pipe connecting the point which was determined to be critical to the trunk.

H. The probability (0 to 1) that any given tributary area will contribute to infiltration in proportion to the length of the collection system in the area. This input requires engineering judgment, assigned by knowledge of code restrictions, construction techniques, and field measurements.

The third set of input data consists of information to describe the trunk line:

A. The line and entry numbers of the upstream end of the pipe being described.

B. The Hazen-Williams coefficient of roughness, the diameter and the pipe length to the next downstream entry.

C. The elevation of the invert at the entry under consideration.

D. An allowance for head lose due to bends, restrictions, manholes, and grade changes.

THE PROBLEM SOLUTION

The flow problem is solved using a limited iteration technique, limited in the sense that the operator of the program has the option to continue interation, stop, or change the problem at regular intervals during processing.

The processing proceeds as follow:

A. All data is entered; calculation of constants is performed.

B. The flows in each lateral and in each section of the trunk line under normal design peak daily flows are calculated.

C. The hydraulic heads at each entry and lateral node are calculated from the flows.

D. The calculated elevations are checked against overflow elevations.

E. Identifying numbers, flows in all branches, elevations and overflow rates are printed.

F. The operator enters an infiltration increment.

G. The infiltration increment is applied to all tributaries and tributary flows calculated.

H. System flows and elevations are recalculated.

I. Elevations above critical points cause calculations of overflows and reduced inputs.

J. System flows and elevations are recalculated and checked for compatibility.

K. Steps I and J are performed three times, output is printed, and the operator is queried for the option to continue the problem or stop.

Two successive outputs which are similar or within operator determined accuracy criteria are used for a stop or change problem decision.

A listing of the program is included in Appendix C. The program shown, which is dimensioned to fit the analysis of the actual system is the largest which can be processed by a computer with a core capacity of 65,000 words. A change in the program to accept a larger problem will require a larger core.

The input data established for the study area is included as Appendix D.

Appendix E is a "run" of the problem with the following assumptions:

A. The ratio of peak-to-average flow is 1.44.

B. The probabilities of infiltration along the two branch lines are approximately equal.

C. The allowed infiltration rates (average) are 0, .008, .01, and .015 gallons/minute/foot of lateral.

The first output is a printout after five iteration cycles of a peak daily flow. The second output is a printout of the system flows at an infiltration rate of .008 after five cycles. More cycles of iteration would eliminate the overflows. The third output are the system flows after five cycles with an infiltration rate of .01. The fourth output is the result of five iterative cycles at an infiltration rate of .015. The fifth and last printout shows the effect of five additional iterative cycles with no change in the infiltration rate. This final model is a good representation of the system under *general* overflow conditions.

The program as presented was designed for use at full-pipe flow conditions and should not be used for computations of varying or uniform flow in partially filled pipes.

SECTION 12

PRELIMINARY INSTRUMENTATION AND FLOW MEASUREMENT

GENERAL

In order to provide a basis for the design of injection tests and to demonstrate the effect of the injections, measurement of flows, overflows, and hydraulic heads is required. The required and desirable characteristics of the measuring elements were defined as follows:

Characteristics and desired features:

A. Ruggedness - As a field instrument, able to withstand rough treatment before and during installation. Preferably able to operate after submergence in sewage.

B. Capability to measure flow in a surcharged line - Efficient use of polymer materials require higher than normal velocities; hence, surcharging is allowed.

C. Non-fouling - Experiments with standpipe and floats in manholes indicated that projections foul rapidly.

D. Accurate - Precision to the limits of the method used.

E. Simple - For servicing requirements.

F. Recording - For unattended long-term measurements.

G. Easily interpretable data - Direct read-out in the units required is preferable.

H. Semi-portable - To make movement from one measuring point to another possible.

I. Adaptable - For mounting in conventional manholes, or remote with taps sealed into the line.

The characteristics and features described above resulted from the need to measure flow, pressure, or head under the following conditions:

A. Flow and/or head measurements through conventional and type "S" manholes.

B. Measurement of vertical flow out of specially-constructed overflow manholes with hinged lids.

C. Flow measurement in overflow pipes (horizontal) ranging in size from 4-inch to 12-inch diameter from beginning of flow to full pipe.

D. Flow measurement in vertical 4-inch overflows.

The instrument market was surveyed, information was solicited from all the major equipment companies and many of the smaller companies. The survey exposed the following general types of flow and head measuring devices:

Float and Stilling Basin

Head measurement by mechanical means, limited to open installations, extreme accuracy possible, subject to fouling.

Purge Tube Pressure

Head or pressure measurement by measuring the pressure required to discharge bubbles against the head, with output converted to mechanical or electrical output.

Ultrasonic Depth Measurement

Measures distance from a known elevation to a liquid-air interface, sophisticated method.

Hook Gauge

Manual or servo-operated to determine surface elevation of a stilling basin, limited in range by mechanical considerations, subject to fouling.

Sounding Rod

Manual, for use in a stilling basin.

Exposed Diaphragm Pressure transducer

Used for level in tanks, electrical output.

Weir

Flow measurement, constructed or prefabricated and used with depth measuring device, in open channels.

Venturi

Flow measurement, restricted to small diameters because of required proportions, required full cross-sectional flow.

Flume

Flow measurement, in open channels.

Propeller-type Steam Meter

Velocity only, requires a minimum stream depth and is subject to fouling.

Ultrasonic Doppler-effect Meter

In-stream velocity measurement, subject to fouling, sophisticated method.

Psuedo-Sound Listening Meter

Relative flow by turbulent noise generation, newly-developed.

Orifice plate

Flow in full pipe, high energy losses.

Dilution Meter (e.g., Fluorometer)

Requires constant rate injection, subject to fouling and interfering substances.

Magnetic Flow Meter

Flow in full pipe, limited to 24-inch and smaller, sophisticated.

Turbine Meter

Flow in full pipe, subject to rapid fouling.

There are, in addition, combinations of and additions to the above list if methods, rather than devices, are considered, but all of the devices in common use, fall in one of the above categories.

A question was raised early in the program concerning the use of the fluorometer, which had been used in an earlier polymer program. Experience with that device had shown that some of the constituents in sewage, and even the pipe wall, can introduce serious errors into flow measurement. For instance, grease fouls the transmission cell wall, suspended colloids are dyed by the injected chemical* and the pipe walls can absorb the dye.

A survey of consulting engineers concerned with doing sewer surveys and flow studies uncovered some interesting information about the quality of flow measurements which they performed for their customers. The majority of flow tests performed use an empirical formula in combination with estimates of line condition, construction data, and water depth measurements to determine flows. The consultants opinion of the accuracy of these methods vary from estimated error of 10- to 50-percent.

The factor which seems to be susceptible to error in the calculation of flow is the line condition or roughness, which coincidentally is the factor which also possesses a large sensitivity in most flow equations.

Based on the above considerations, it was decided to use float-type level recorders and dip-sticks in combination with tables and nomographs to supplement a system of interconnected bubble-purge level meters to be installed on the sewer trunk.

The bubble purge level meters are a variation on a system used by some engineers for field survey work. The system consists of a bottle of liqufied carbon dioxide discharging gaseous carbun dioxide through a regulator into a tube equipped with a sensitive pressure gauge. The devices built for this project make use of the fact that a bottle of liquid carbon dioxide holds essentially a constant pressure so that a constant rate of discharge can be obtained by venting through an orifice.

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*Buchtela, K., et al, "Comparative Investigations into Recent Methods of Tracing Subterranean Water", National Speleological Society Bulletin Vol. 30, No. 3, July 1968 (70).

The pressure gauge was replaced with a semiconductor strain-gauge pressure transducer and associated circuitry to provide an analog signal proportional to the depth of submergence of the purge tube. Figure 25 shows one of the devices installed in a manhole.

The signal was brought out by drilling a hole through the manhole wall near the top, through which a cable was passed. Because of the remote locations of the measuring stations, it was not possible to use existing telephone lines, so cables were trenched into the ground, run overhead, or buried in pavement as required. The overhead lines for which natural support was used were the most troublesome in that breakage sometimes occurred during the windstorm which accompany many of the thunderstorms in the test area. The buried lines have given no problems.

The signal cables from groups of measuring points were brought to centrally-located recording stations. One of the stations is shown in Figure 26. This station consists of a power supply to provide the operating voltage to all of the remote sensing locations, a signal timer to sequentially connect each signal source to a recorder, and a single-channel strip chart recorder. The multiple signals are recorded side-by-side with a calibration signal and a zero check. An example of the record is shown in Figure 27.

In those cases where a convenient entry, such as a manhole, was not available, the level sensors were chained to convenient structures or trees and the purge tube was run to the sensing location. In small pipes, the tube end was sealed in place. For type "S" manholes (pressure manholes) in the stream bed, iron pipe standards were welded into the manhole covers and guyed to the bank to guard against the bombardment of flotsam during flood stage. The purge tube was then inserted into these standpipes.

The instruments which were exposed to gross temperature changes required a modification to isolate the pressure transducer from thermal stresses in the support. This was done by mounting the transducer in a material having a low coefficient of thermal expansion. This modification was not necessary for those instruments mounted in the relatively constant environments of a conventional manhole.

One additional method of flow measurement which was used during the field survey is the "salt velocity" method. This technique has been described by John Schmidt* for use in determining discharge coefficients and is very simple to apply to field measurement problems. The technique avoids the clogging and mechanical interference caused by solids when a rotating-cup velocity meter is used.

It should be kept in mind that the methods chosen for "flow" measurements during the preliminary injection tests did not have the capability of performing during the tests, only before and after injections. This is because assumptions made in designing most water flow-measuring devices assume the properties of the fluid as Newtonian, a necessary condition which is violated when the flow is non-Newtonian.

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* Schmidt, O. John, "Determination of Discharge Coefficients by the Salt-Velocity Method"Journal Water Pollution Control Federation, 1969.

Fig. 25. Purge-Tube Level Meter Installed in Conventional Manhole

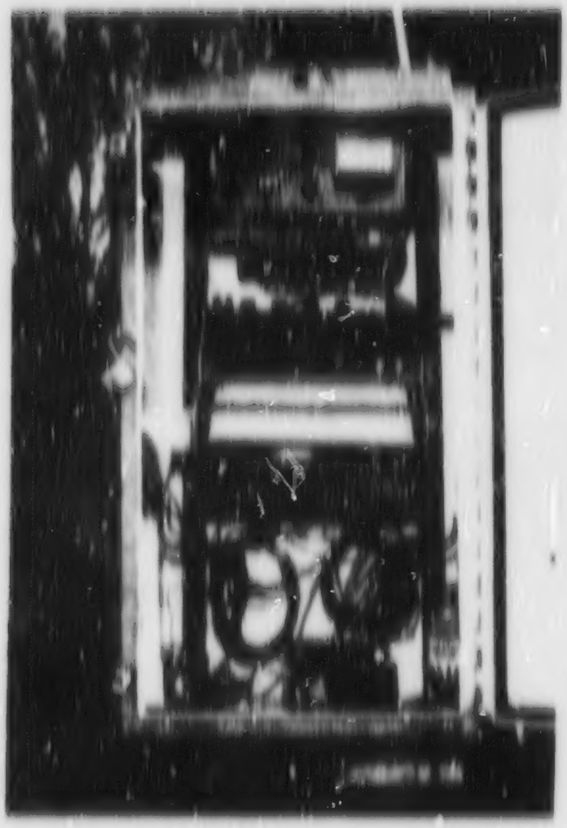

Fig. 26. A Multiple-Input Recording Station

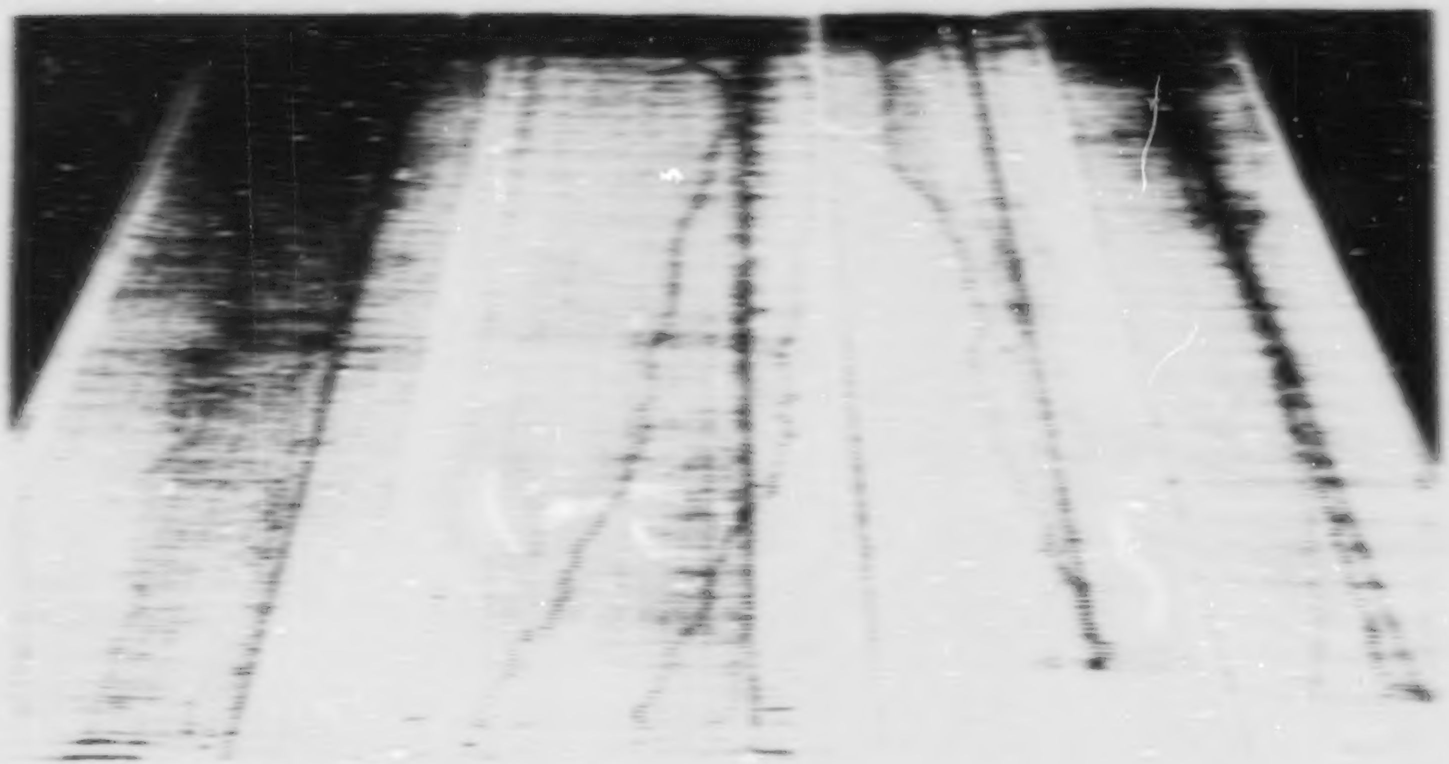

Fig. 37 Example Recording Showing A Building and Receding Storm Flow

SECTION 13

RESULT OF POLYMER INJECTION IN SURCHARGED GRAVITY LINES

The purposes of performing polymer injection tests were as follows:

1. To verify that the overflows from the Bachman trunk sewer could be eliminated or reduced by the injection of friction-reducing chemicals.

2. To determine design criteria concerning the injection rate for the permanent injection station.

3. To establish a suitable location for the permanent injection station.

Two injection locations were chosen for the 15" and 18" branches of the trunk sewer, one for the most desirable location and one to check the effect of injecting the polymer far upstream of the required line section. One injection location on the 24" line was chosen to check the effectiveness of the polymer after being subjected to the destructive forces of a long run of pipe. These five injection locations are indicated on the area map of Figure 20 A. A secondary consideration in the selection of the temporary injection points was the presence of an existing entry into the line.

All data gathered during the early stages of the program indicated that the problem line section was the 2,590 feet of 24" line at the upper end of Bachman Trunk and the 18" line of Bachman Branch. This indicated the need for injection on the Bachman Branch, a location which would also satisfy the requirement for friction reduction in the 24" line.

Figure 28 is a surcharge-time plot for a complete storm flow as recorded by one of the monitoring stations on March 20, 1970. The average rainfall over the test area was less than one inch and the rainfall was of low intensity so that the rise and fall are gradual. The overflows caused by this storm were short-lived and of low total volume.

Conversely, the rainfall of April 25 was short and intense and produced the flood waves shown in Figures 29 and 30. Notable is the quick rise and the long decay recorded on both of these graphs. The graph of Figure 29 was produced by a station about 8300 feet upstream of the station which produced the record of Figure 30. The lag in the front of the wave is indicative of the distance between the two points on the line. The results of an injection is shown on Figure 29 about hour 15. The same injection appears on Figure 30 at hour 17. The storm peaks shown in Figures 29 and 30 are typical and represent flows at the downstream measuring point of 10.7 MGD at peak. This compares to a design of about 10.7 MGD with new pipe conditions.

Table 14 gives the dates, injection locations, injection rates and results in terms of maximum head reduction. The locations are keyed to the map of Figure 20 The type of slurry used is also noted.

The philosophy of the injection tests was to inject polymer at the prescribed rate until the head reduction ceased, then stop injection and allow the system to come back to equilibrium. This procedure was repeated at least once if possible to guarantee that any reduction in head was truly related to the injection of polymer and not caused by a coincidental phenomenon.
Figures 31, 32, and 33 show the results of some of the tests as observed from the location noted on the figures.

Injections at locations four and five were not performed. There were no significant surcharges or overflows on this branch line during the conduct of the program.

Figure 33 indicates that a polymer rate of 4.5 pounds/minute is in excess of that required for actual control of overflows. This injection halted all overflows on the Bachman Trunk and the Bachman Branch. The most efficient injection rate would be that which holds the head at a "safe" level below the overflow. Injection of sufficient quantities of material to put all the flow in the conduit would not be economical for any purpose except experimentation.

TABLE 3.4 RESULTS OF POLYMER INJECTION TESTS

TEST NO.	DATE	INJECTION LOCATION		INJECTION RATE (lbs./min.)	PRE-INJECTION FLOW RATE (gpm)	POST-INJECTION	
		NUMBER	STATION			REDUCTION (Ft.)	LOCATION
1	27 April 70	1	25+40^1	1.2	7100	2	25+40^1
2	30 May 70	1	25+40^1	ABORTED BECAUSE OF EQUIPMENT FAILURE			
3	2 Sept. 70	1	25+40^1	1.5	4600	1.0	25+40^1
4a	2 Sept. 70	1	25+40^1	2.25	4500	1.75	25+40^1
4b	2 Sept. 70	1	25+40^1	2.25	4900	1.5	186+25^2
5a,b,c	2 Sept. 70	–	175+66^2	2.25	8000	2.0	186+25^2
6	21 Sept. 70	3	128+00^2	2.25	3600	0.5*	25+40^1
7	23 Sept. 70	1	25+40^1	4.5	5000	4	29+25^1

* A large portion of the polymer was lost through an intervening overflow

** All overflow stopped

[1] Stationing on Bachman Branch Line

[2] Stationing on Bachman Trunk Line

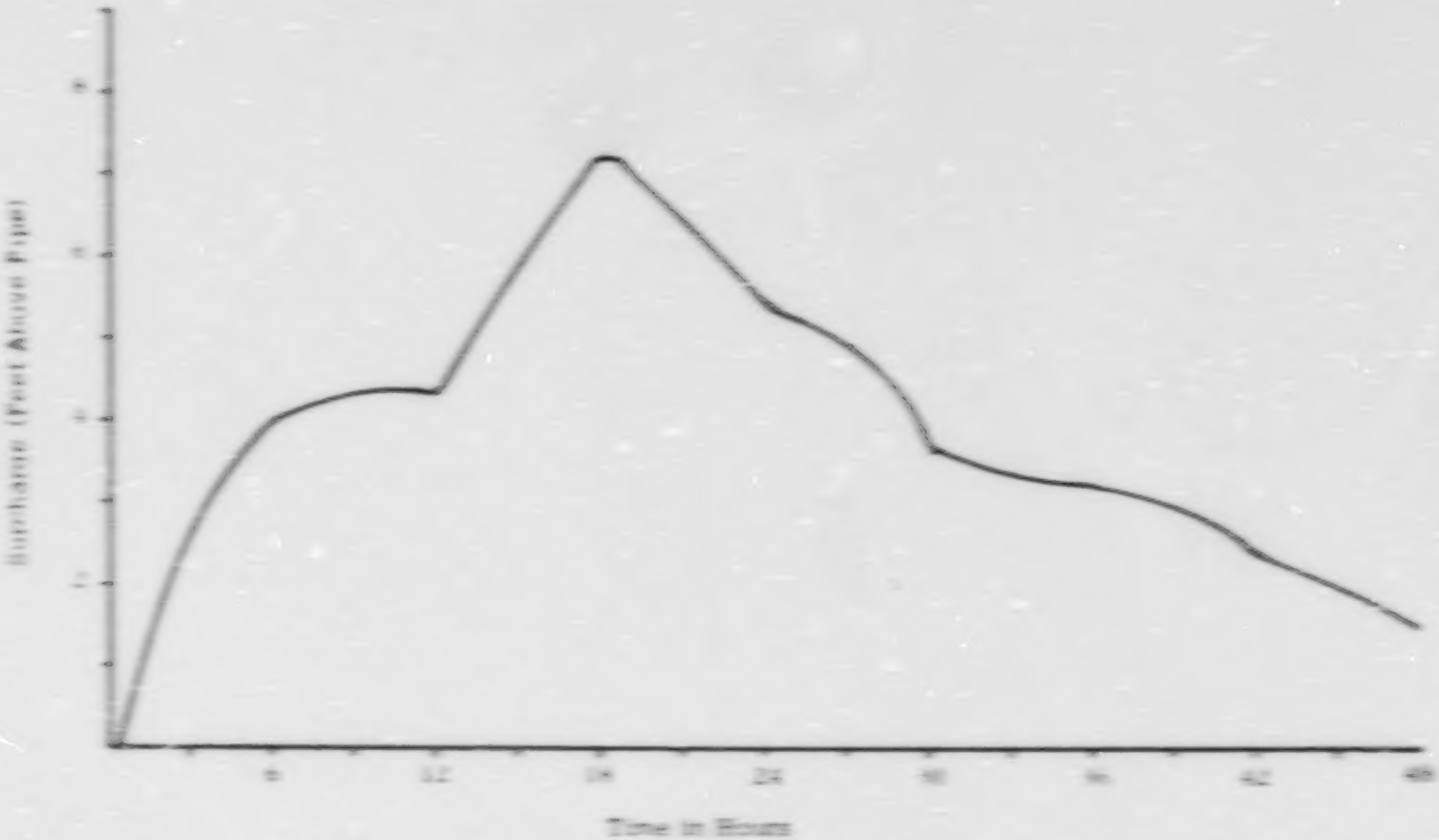

Figure 28. Storm Stage at Station 164-33 (Bachman Trunk at Northwest Highway) on 25 March 1970

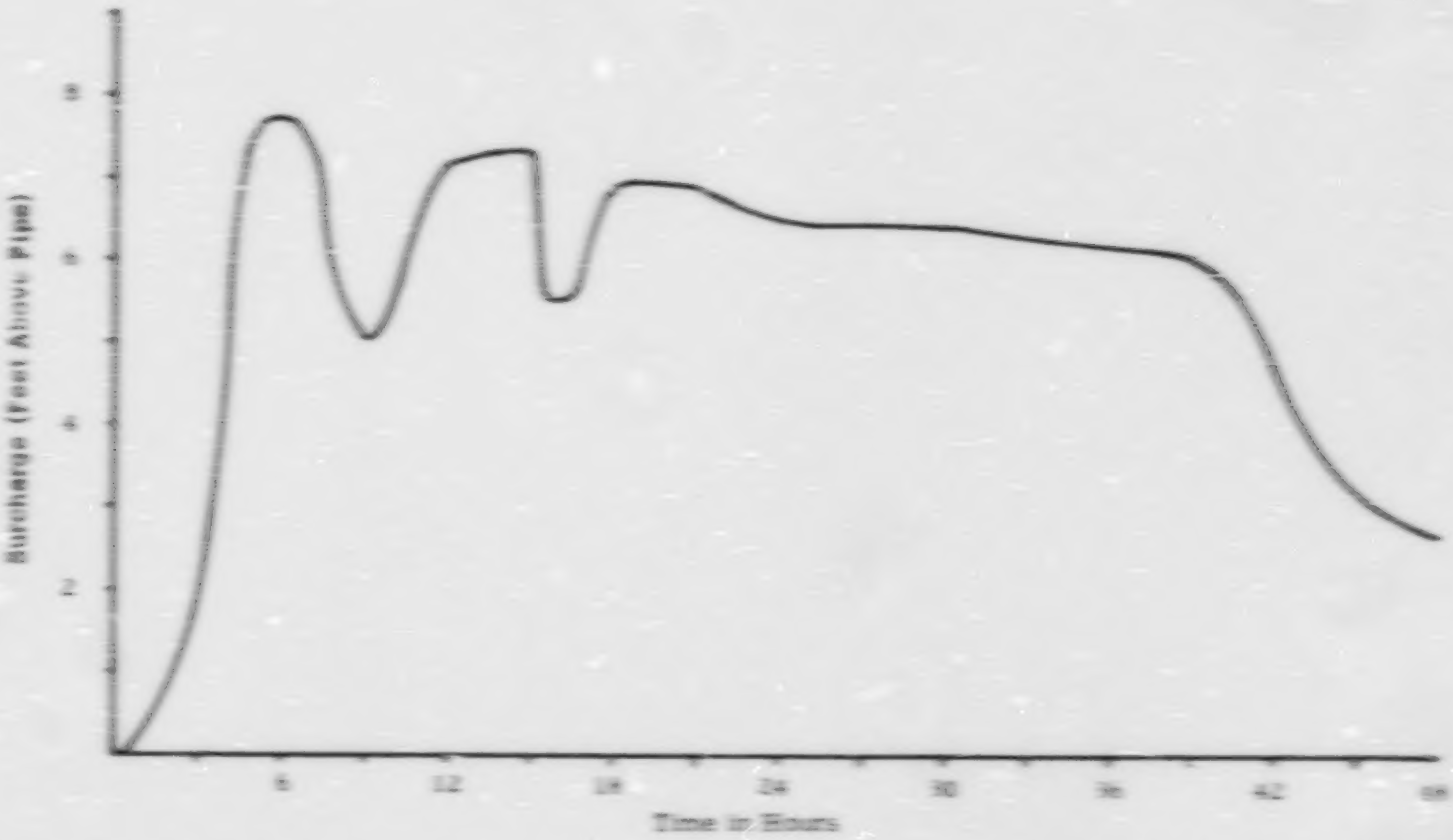

Figure 39 - Storm Stage at Station 35 + 40 (Bachman Branch at Walnut Hill Lane) on 25 April 1970

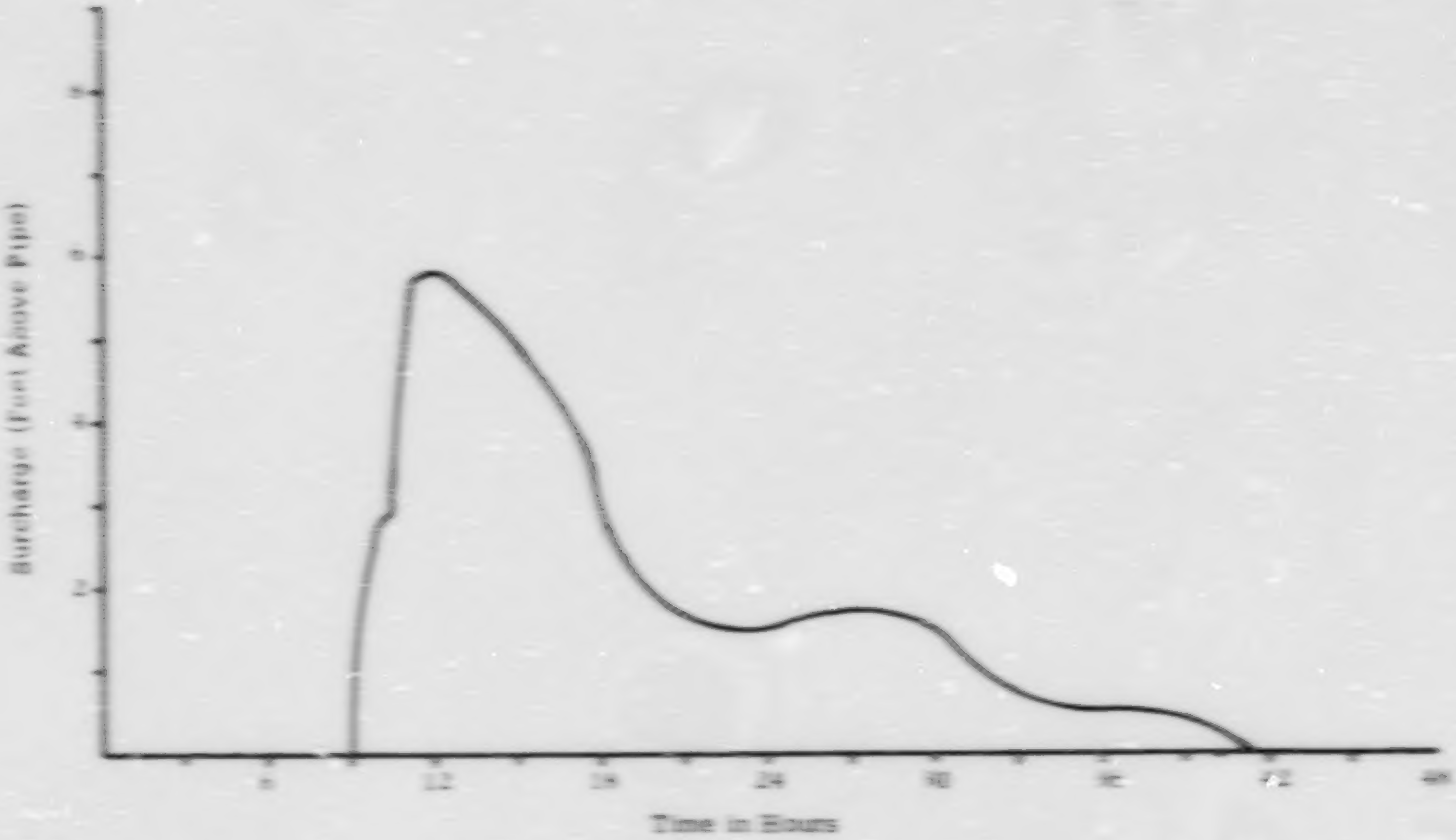

Figure 38 Storm Stage at Station 164 + 33 (Bachman Trunk at Northwest Highway)
on 25 April 1970

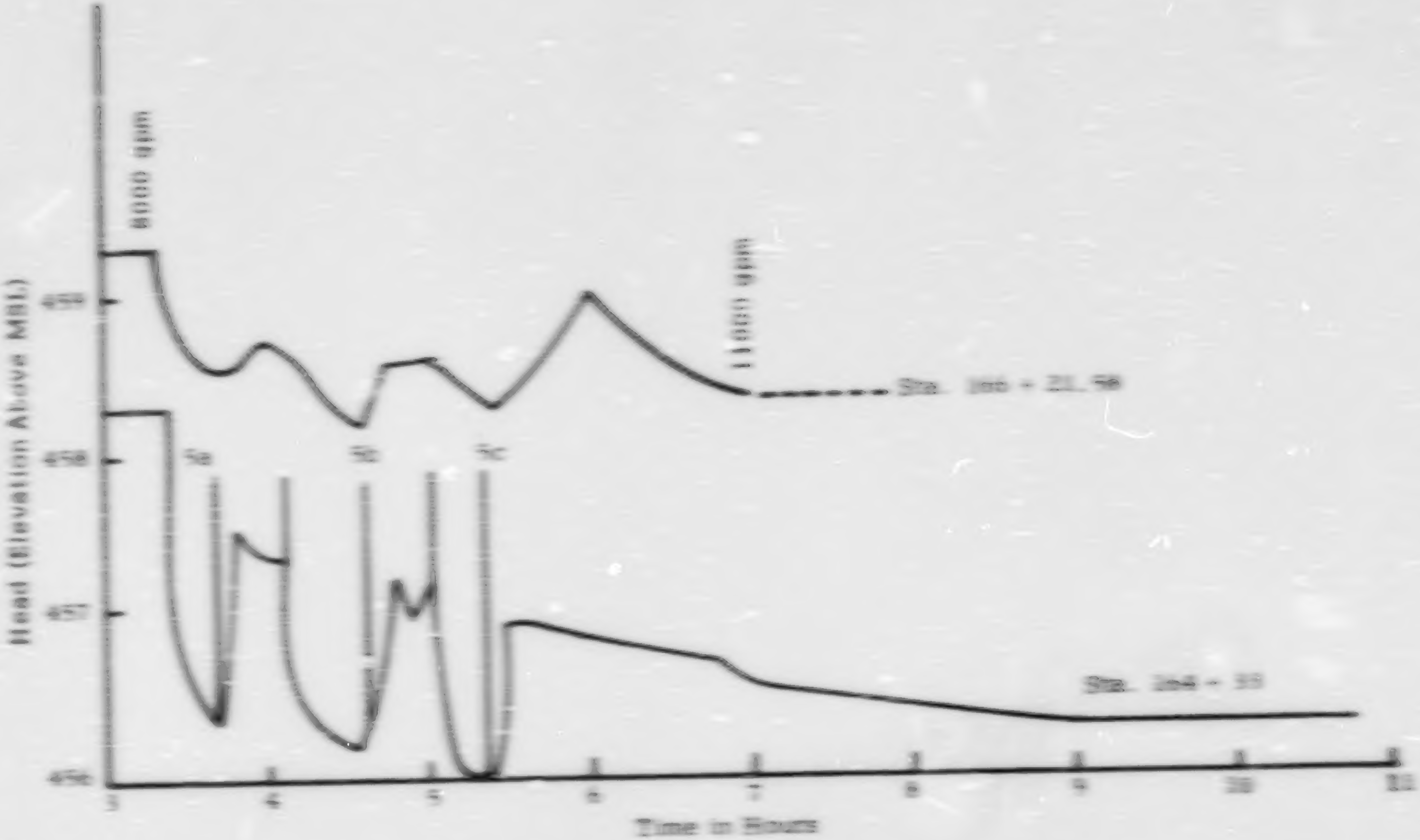

Figure 38 Results of Injection Test 5 on Heads at
Stations 164 + 33 and 166 + 21.58 (Below Northwest Highway)

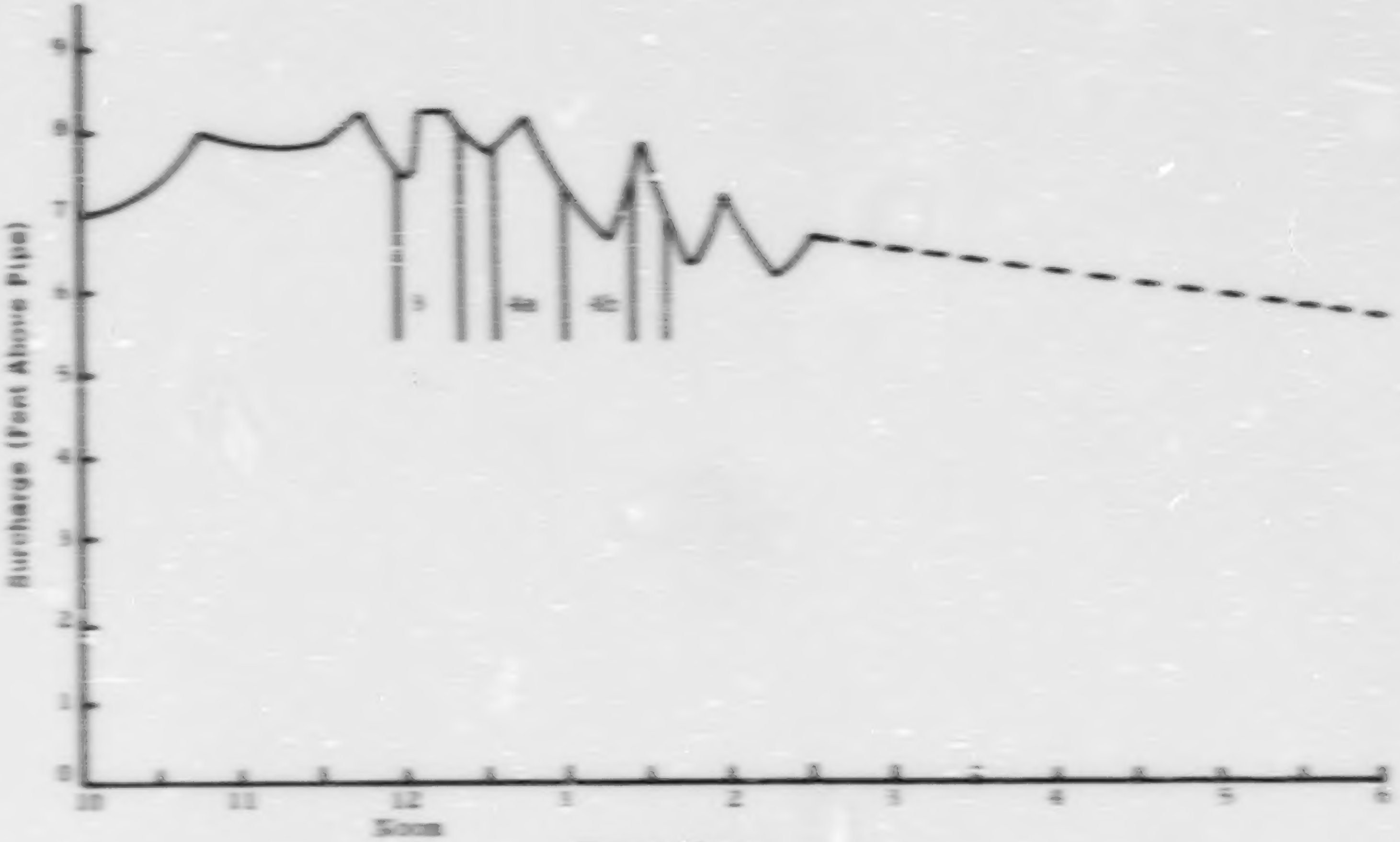

Figure 32. Results of Injection Tests 3, 4a, and 4b on Surcharges at Station 35+40
(Bachman Branch at Walnut Hill Lane)

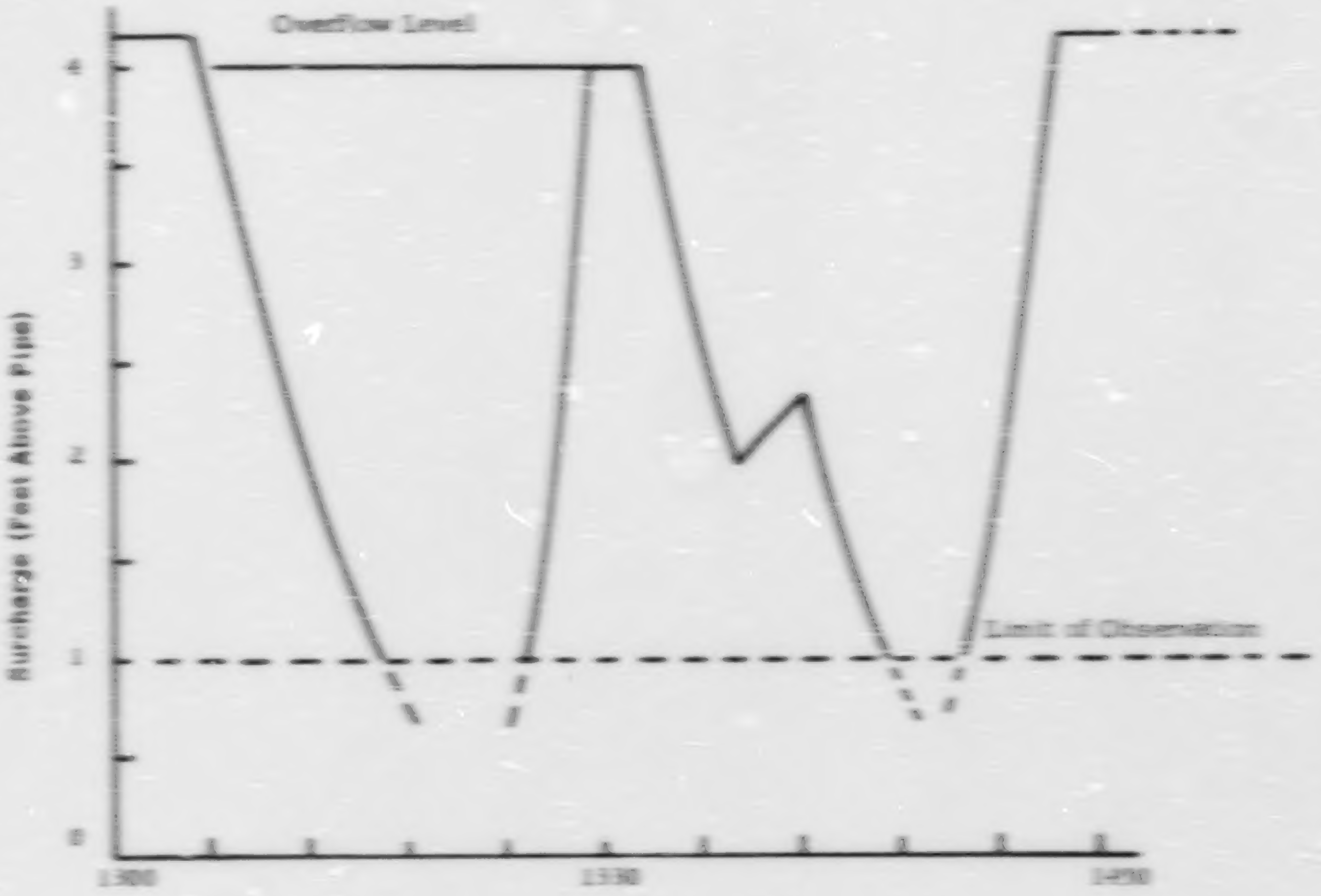

Figure 33 Effect of Polymer Injection Test 7 on 25 Sept. 1979
on Overflow at Station 29 + 35 (Bachman Branch below Walnut Hill Lane)

SECTION 14

RESULTS OF POLYMER INJECTION IN 6" FORCE MAIN

While the main emphasis of this program is the overflow reduction in surcharged gravity sewers, a portion of the program required the determination of head loss reduction or pump flow increase possible through the use of polymers in a lift station.

The lift station selected for tests was the Riverwood Station in East Dallas. The station serves a small residential area generating daily flows of about 30,000 gallons. This flow is sufficient to require the pump to operate for about 3 minutes twice an hour normally and more often during peak periods. This site was chosen because it could be instrumented readily and effectively and was representative of the many "package plants" in the city. The prefabricated lift station was installed adjacent to a sump which stored the sewage between pumping cycles. The sump was emptied by one of the two pumps, pumping the sewage through a 6-inch cast iron pipe for some 2,000 feet over a hill to a suitable collector line. Table 16 lists the nameplate data on the pumps.

TABLE 16. LIFT STATION PUMP DATA

Make	Smith & Loveless
Size	4 B
Capacity	250 GPM
Speed	1760 RPM
Head	65 feet
Power	15 Horsepower
Phase	3
Voltage	220-440
Current	58.6 - 19.5

A review of the design criteria indicates the following:

1. Design static head = 35 feet of water
   = 15.2 psi

TABLE 16 RESULTS OF LIFT STATION TESTS

(Performed Between March 10 and March 19, 1971)

Polymer Application Rate (lb/min)	Based On Initial Polymer Conc. (ppm)	Based On Final Polymer Conc. (ppm)	Initial Flow (GPM)	Velocity (ft/sec)	Discharge Pressure (psi)	Flow Increase (%)
0	0	0	260	2.95	26	0
.26	120	90	350	3.97	25	34.6
.4	185	125	385	4.37	24	48.1
.74	350	210	425	4.82	24	63.5

2. Total head at 400 gpm = 62 feet of water
= 26.9 psi

A 6-inch Foxboro magnetic flow metur was installed in the pump discharge line to accurately measure the flow. A Westinghouse type 44 recording ammeter was connected to the pump leads to measure current variations. A corporation stop was installed in the pump suction line for the polymer application. The lightweight variable flow polymer injection device was used to apply polymer to the pump suction during tests.

The low normal flow of sewage to the sump was augmented by a fire hose discharging into the last manhole on the line leading to the sump. This augumented flow resulted in shorter emptying cycle, with the pump operating every ten minutes. This allowed more tests to be performed over a shorter period.

Fifteen pumping cycles were observed of the augmented flow with no polymer. The observed flow rate, and discharge pressure gave base line data upon which to compare the polymer data. It should be noted that at the rated total head the discharge was 35% low. Table 16 , Results of Lift Station Tests, lists the flow data both from the base line tests and the subsequent polymer tests.

The polymer tests wure performed with applications of .26, .4, and .74 pounds per minute of polymer. Five tests each were performed using .74 and .4 pounds per minute of polymer with the results as shown on Table 16. The polymer feed line plugged during the second tests on the .26 series, therefore, the results shown are for only one test.

Following the polymer tests, the system was allowed to purge the polymer from the lines, and the base line data observed. The non-polymer flow rate and pressure returned to that originally measured.

The change in flow rate from polymer application increased the electrical current draw of the pumps. The ammeter showed normal flow to require 19.5 amperes as stated on the nameplate. The highest polymer application, .74 pounds per minute, resulted in a current draw of 22 amperes or an increase of 12.5%.

Figures 34 and 35 are reproductions of recorder charts which show the flow rates with no polymer added and at the maximum injection rate. Chart values should be multiplied by 2 to obtain actual flow rates. The charts were run at an accelerated rate so that a complete rotation occurs every 24 minutes rather than 24 hours. This permitted the average flow rates to be calculated from the volume of the pump from pump turn-on level to pump turn-off level. In this manner, the recorded output of the flowmeter was verified. It should be noted that the "spiking" recorded is an actual phenomenon, apparently an amplification of normal short-term oscillations around the normal flow* , or a result of varying solution efficiency of the injected slurry.

One notable aspect of this experiment is the relationship between flow rate and discharge pressure. When working in a gravity sewer, it is usually desirable to cause a decrease in head while holding the flow rate constant; on the other hand, for polymer applications to force mains it is desirable to increase pumping capacity for a given discharge pressure. This is exactly the result shown by the data; significant increases in flow rate with negligible changes in discharge head.

Figure 36 is a graph relating polymer injection rate to percent flow increase. The bottom line represents the results of the field tests, and the top line represents a laboratory test of the same material in a six-inch diameter line. It should be noted that although the shape of the graphs are similar, the flow increases for a given injection rate were significantly lower for the field tests.

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*Rouse, Hunter, "Engineering Hydraulics", John Wiley and Sons, Inc., New York, 1950, p. 86.

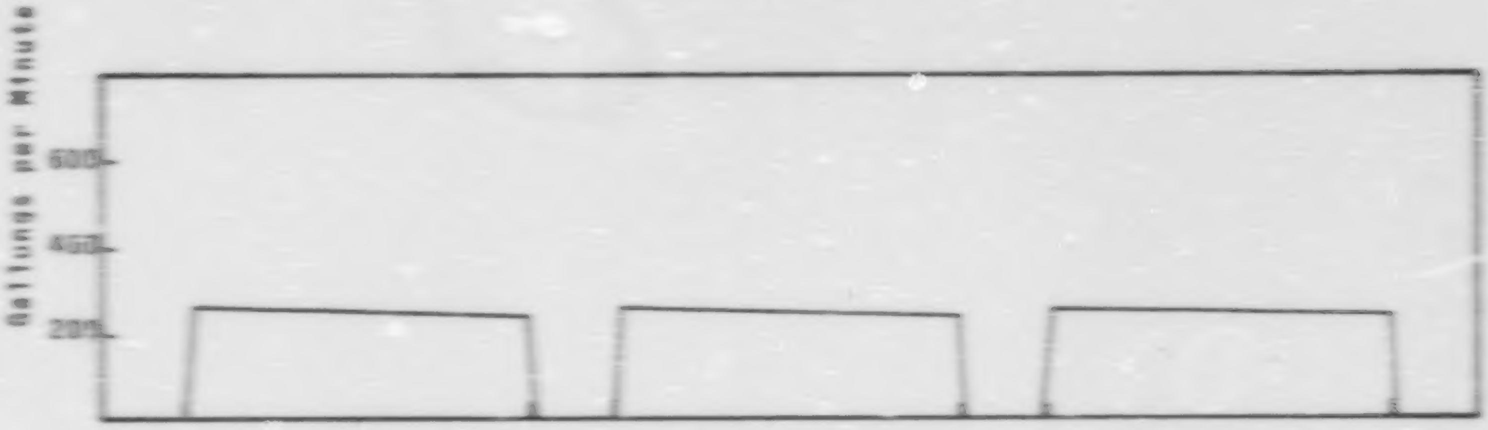


Figure 34
No Polymer Added

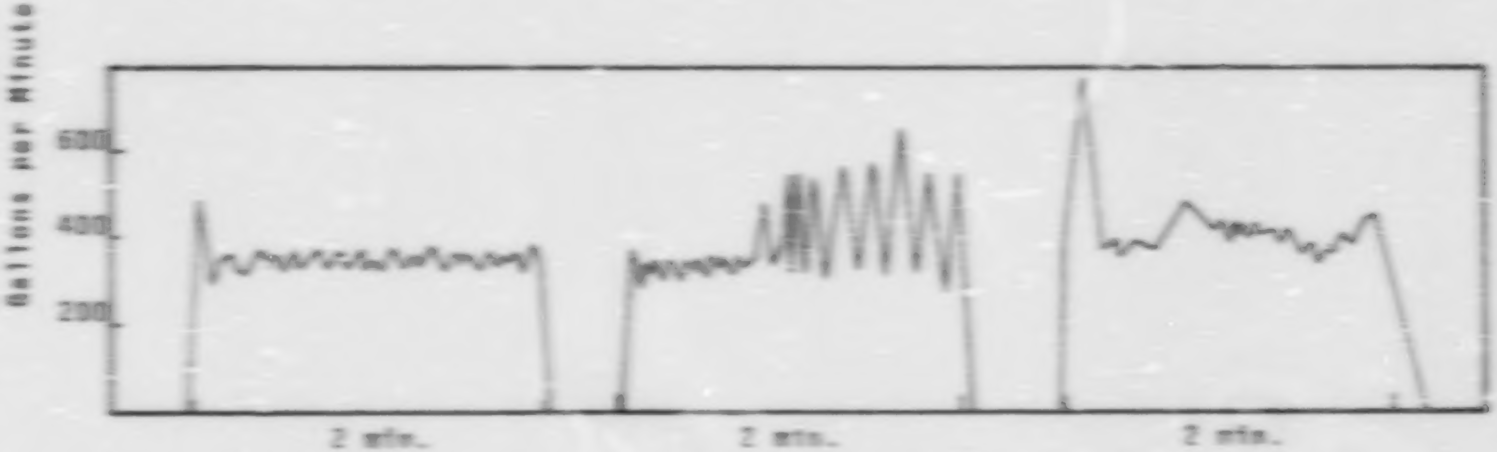


Figure 35
Polymer added at 0.74 at 0.74 lbs/min
[Maximum injection rate]

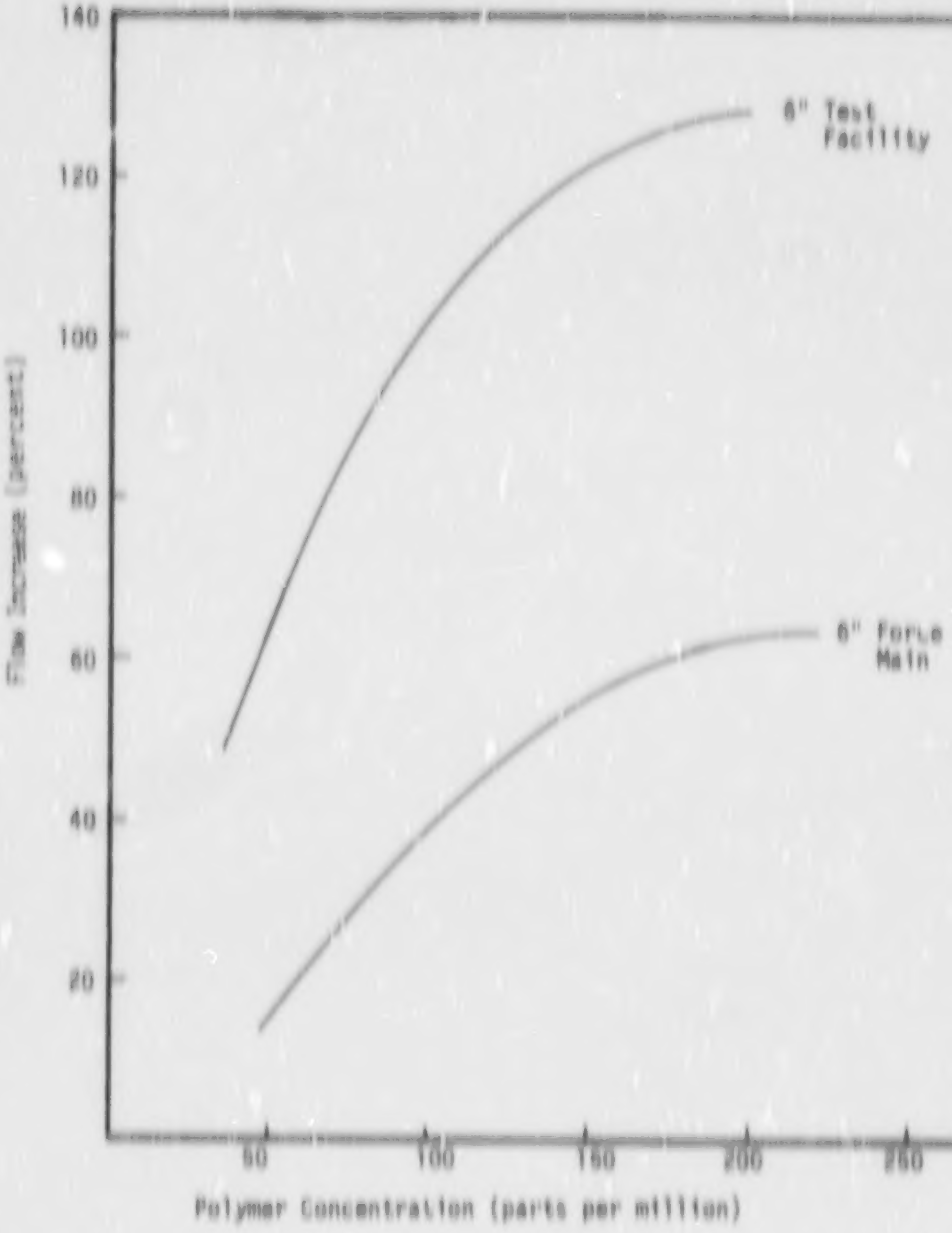


Figure 35. COMPARISON OF RESULTS FOR
6" TEST AND FORCE MAIN TESTS

SECTION 15

THE CONSTRUCTED INJECTION STATION

GENERAL DESCRIPTION OF THE FACILITY

The Bachman Polymer Injection Station is a fully automated facility for the storage, mixing, and injection of selected turbulent friction-reducing chemicals which generally are amorphous, water-soluble, high molecular weight polymeric substances. The facility can be divided into six functional groups as follow (Refer to Figure 37.)

A. Polymer de-drumming - Consists of a 600 cfm centrifugal blower driven by a 3 horsepower, three phase electric motor, 50 feet of three inch diameter flexible hose and a centrifugal separation system which is an integral part of the storage hopper.

B. Polymer storage - Consists of a cylindrical tank with a conical bottom, lined with urethane foam insulation and equipped with a dessicant-type dehumidifier and humidistat.

C. Polymer feed and metering - Consists of a vibrating cone hopper bottom and a helical screw volumetric feeder equipped with a variable-speed DC drive motor.

D. Polymer dispersing and injection - Consists of a water jet eductor, buffer tank, and a positive displacement gear pump with a three-phase AC drive motor.

E. Control circuitry - Consists of motor starter control relays, time sequencing relays and two DC motor speed controls.

F. Instrumentation - Consists of one 18" magnetic flowmeter, three bubble-type level transducers, one thermocouple temperature transducer, one elapsed time meter and one six-channel scanning strip chart recorder.

OPERATING PRINCIPLES OF THE POLYMER INJECTION STATION

A. Normal Operation

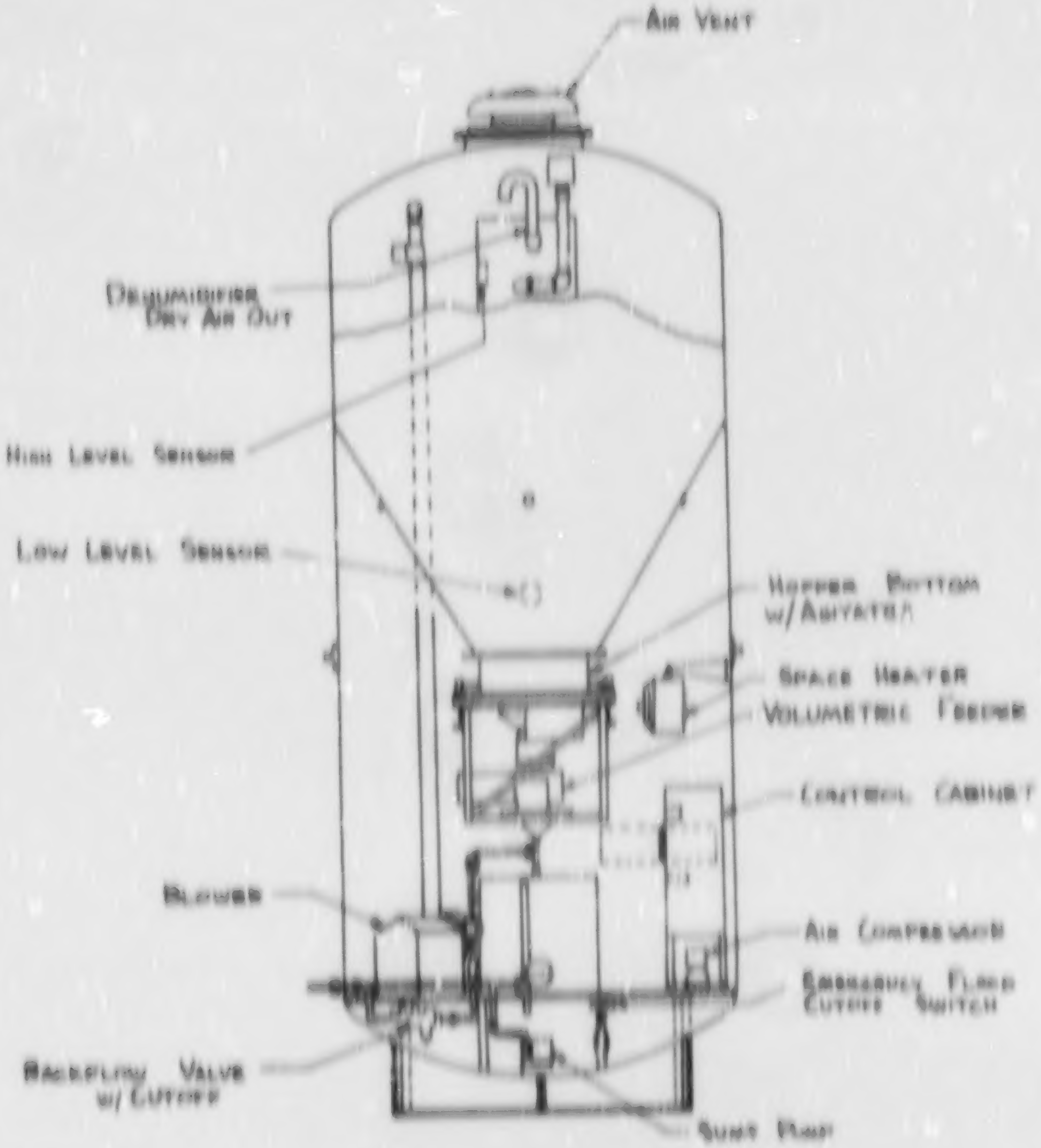

Air Vent
Dehumidifier
Dry Air Out
High Level Sensor
Low Level Sensor
Hopper Bottom
w/Agitator
Space Heater
Volumetric Feeder
Control Cabinet
Blower
Air Compressor
Emergency Flood
Cutoff Switch
Backflow Valve
w/Cutoff
Sump Pump

FIGURE 37

ELEVATION OF POLYMER INJECTION STATION
LOCATING MAJOR COMPONENTS

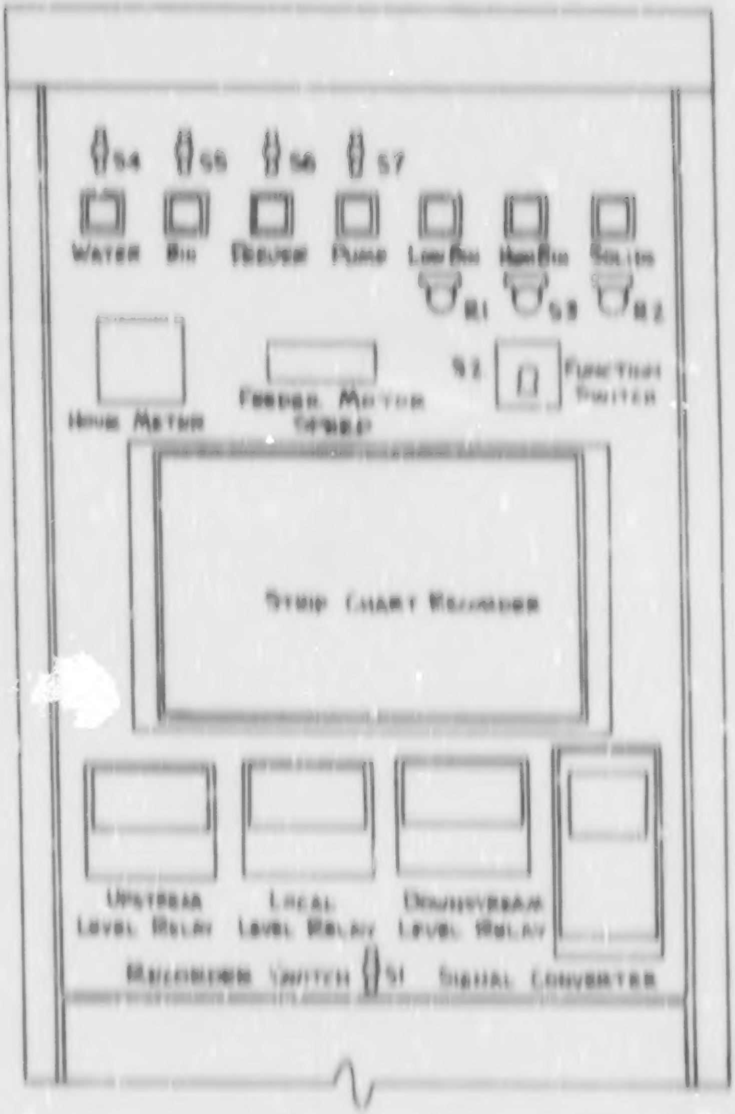

S4
S5
S6
S7
WATER
BIN
DRIVER
PUMP
LOW BIN
HIGH BIN
SOLIDS
R1
S3
R2
HOUR METER
FEEDER MOTOR SPEED
S2
FUNCTION SWITCH
STRIP CHART RECORDER
UPSTREAM LEVEL RELAY
LOCAL LEVEL RELAY
DOWNSTREAM LEVEL RELAY
RECORDER SWITCH
S1
SIGNAL CONVERTER

FIGURE 30
SKETCH OF MAIN CONTROL PANEL
SHOWING THE LOCATION OF
CONTROLS, METERS, AND INDICATORS

Operation of the polymer injection mechanism is initiated by a rise in the level of the free water surface at any one of the three level-measuring sensors - upstream at Royal Lane, downstream at Brookview Lane, and in the vault which also houses the primary flow measuring apparatus. These levels are converted to a 4 to 20 milliampere signal and displayed on the three Beede Meters located immediately below the multipoint recorder on the instrument panel. (Refer to Figure 38) These three meters are "percent of full-scale" indicators, with 100 percent corresponding to a head of 150 inches of water above the sensing point. These meters are equipped with two manually-set relay pointers; green for low set-point and red for high set-point. The position of these pointers determine the indicated level at which two normally open sets of relay contacts will close. Figure 39 is a schematic of the process control system.

During stand-by operation of the station, with the "Run-Auto-Test" switch in the "Auto" position, signals are received from the three level transducers and the magnetic flowmeter, but these signals are not recorded. If the indicator pointer (black) of any of the three meters passes the green pointer, the recorder is activated. The signals recorded and their symbols are: (1) Flow; (2) Sewage Temperature; (3) Local Level; (4) upstream Level; (5) Downstream Level; and (6) Polymer Feeder Speed.

The red pointers on the three level meters are always set at a higher scale position than the green, and their positions determine at what water level the injection station goes into an "Active" status. When the indicator pointer (black) passes any one of the three red pointers, the station will start operation. Operation will continue until all three indicators are at a lower scale position than the red set-point, assuming that none of the emergency shutdown devices are activated.

Once a signal activates the station, the following sequence is executed automatically:

1. The solenoid valve opens, allowing process water to flow through the polymer dispersing eductor, thereby setting up an air flow through the intake port of the eductor, and simultaneously closing the pressure switch on the feed water line.

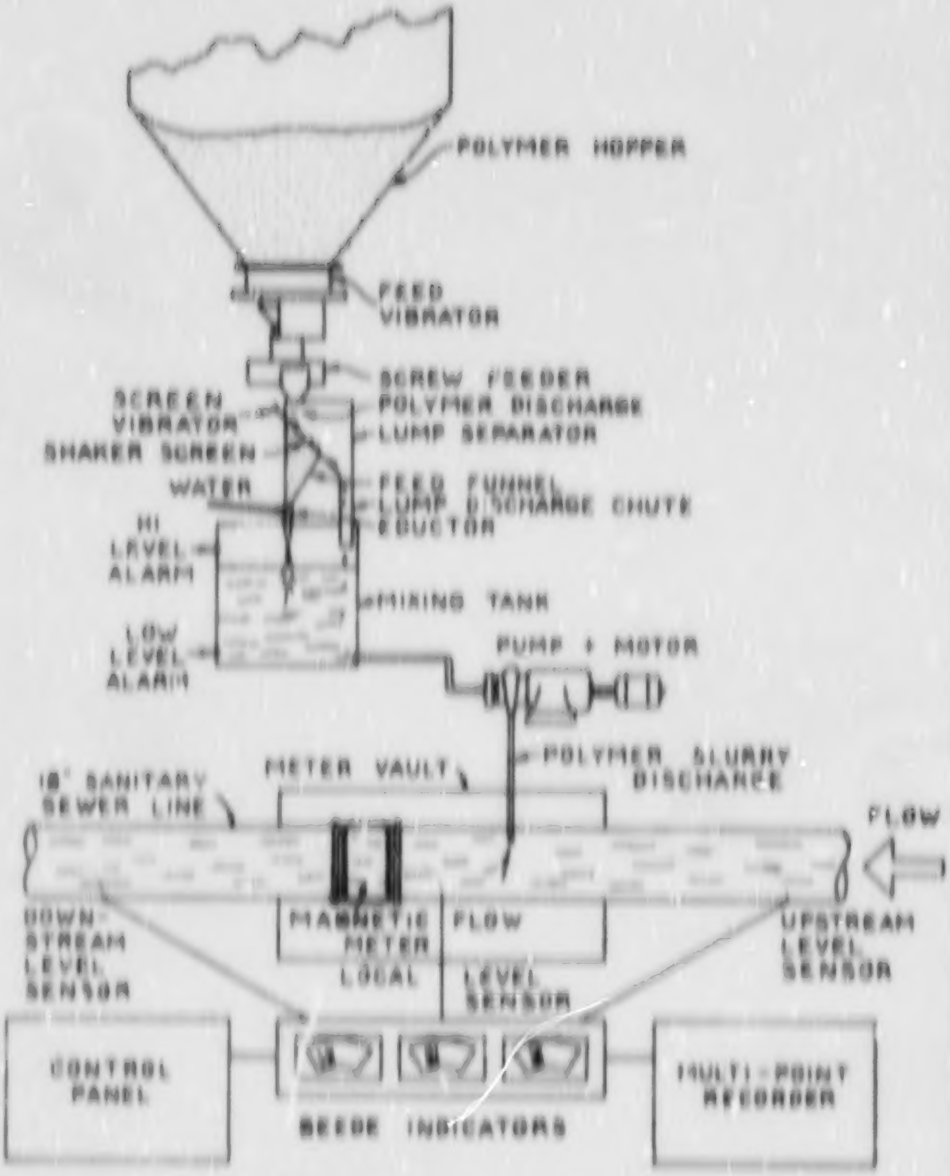

POLYMER HOPPER
FEED VIBRATOR
SCREW FEEDER
SCREEN VIBRATOR
POLYMER DISCHARGE
LUMP SEPARATOR
SHAKER SCREEN
FEED FUNNEL
WATER
LUMP DISCHARGE CHUTE
EDUCTOR
HI LEVEL ALARM
MIXING TANK
LOW LEVEL ALARM
PUMP + MOTOR
POLYMER SLURRY DISCHARGE
METER VAULT
18" SANITARY SEWER LINE
FLOW
DOWN-STREAM LEVEL SENSOR
MAGNETIC METER
FLOW
UPSTREAM LEVEL SENSOR
LOCAL
LEVEL SENSOR
CONTROL PANEL
BEEDE INDICATORS
MULTI-POINT RECORDER

FIGURE 39

SCHEMATIC OF PROCESS CONTROL SYSTEM, BACHMAN POLYMER INJECTION STATION

2. When the pressure switch closes, a time-delay relay (adjustable 0 to 180 seconds) will start.

3. At the end of the pre-set period, a time-delay relay closes, activating the bin activator and polymer feeder.

4. The speed of the polymer feeder is determined by any of five manually selected signals. The signal is selected with the large rotary switch located on the control panel at the upper right. If this switch is placed in the "Manual" position, feeder speed is determined by the potentiometer to the left of the "Run-Auto-Test" switch. If this switch is placed in the "Flow" position, the feeder speed is determined by the output signal of the magnetic flowmeter and a constant proportion of polymer to sewage flow will be maintained. If the selector switch is placed in the "Up stream", "Local", or "Downstream" positions, the feeder speed will be determined by the corresponding level signal. This would normally be the mode of operation, and the position chosen is determined by establishing the most critical level which must be maintained. Regardless of the source of the feeder control signal, the speed of the feeder is indicated on the tachometer located on the control panel, and the speed is recorded as percent of full scale on the strip-chart recorder.

Note: The hour-meter located on the panel is operational when the polymer feeder is activated. The reading of this meter can be utilized as an aid to determining polymer usage.

5. The injection pump is activated by the lower sensor mounted in the side of the stainless steel mixing tank. A thermal-delay relay is incorporated in the starting circuit, so the pump will not start until the sensor has been covered by the process fluid for the timing period of this relay. The pump will continue to run until the fluid level drops below this sensor. The pump speed is controlled by the potentiometer to the right of the "Run-Auto-Test" switch. The pump will normally run at such a speed that fluid is removed from the tank at the same rate that it is being added.

6. When the level in the sewer drops below the level which initiates the operation as described above, the bin activator and polymer feeder will stop immediately. The process water continues to run for a period of time determined by a second time-delay relay adjustable from 1 to 30 minutes in order to wash down solids which may be clinging to the sides of the tank. At the end of the delay period, the water flow will stop (solenoid valve closes) and the injection pump will stop when the lower sensor is exposed.

7. The station now returns to a "Stand-By" status.

B. Tests, Indicators, and Emergency Shutdown

The operation described as normal sequence above can be initiated for test purposes by placing the "Run-Auto-Test" switch in the "Run" position to start the sequence. Turning the switch to the "Auto" position will start the wash-down sequence.

Seven indicator lights on the main control panel indicate the status of the station at any time. When the station is in a "Standby" mode, none of the indicators should be illuminated. The meanings of each light, reading from left to right on the panel, are as follows:

1. "Water" - This indicator is lit at any time that the solenoid valve should be open. Certain interlocking safeties may stop the water flow but leave the indicator lit. These are: (a) flooded sump; (b) overflowing mixing tank; (c) no water pressure; and (d) a full polymer mixing tank (upper sensor covered).

2. "Bin"- This indicator is lit when the bin activator should be running. A lack of water pressure for one of the reasons enumerated above, or a stoppage in the polymer disperser eductor will stop the bin activator and leave this indicator illuminated.

3. "Feeder"- This indicator is lit when the feeder should be running. Any of the abnormal conditions described under "Bin" will also stop the feeder.

4. "Pump" - This indicator is lit if the fluid level in themixing tank is above the lower sensor and the injection pump should be operating.

5. "Low Bin"- If this indicator is on, there is less than ten cubic feet of polymer in the storage bin.

6. "High Bin"- If this indicator is on, the storage bin is filled to or past, the recommended maximum fill level.

7. "Solids Level"- This indicator is illuminated if the polymer disperser eductor will not accept the polymer feed. That is, the feed funnel is plugged.

C. The Injection and Metering Vault

Because the sewer line into which the polymer is injected is located in the bottom of a creek channel, it was necessary to construct a vault to house the required metering equipment. It is in this vault that the connection of the discharge from the metering and mixing equipment was made.

In joining the fiberglass-reinforced pipe to the concrete sewer line, a polyethylene heat shrinkable tubing was used as discussed in EPA Report No. "Heat Shrinkable Tubing for Sewer Pipe Joints."

Figure 40 is a plan view of the injection and metering vault showing the location of major components, including:

1. Temperature transmitter for sewage temperature.
2. Magnetic flowmeter for sewage flow.
3. Pressure transmitter for the "local level".
4. The polymer slurry feed line.

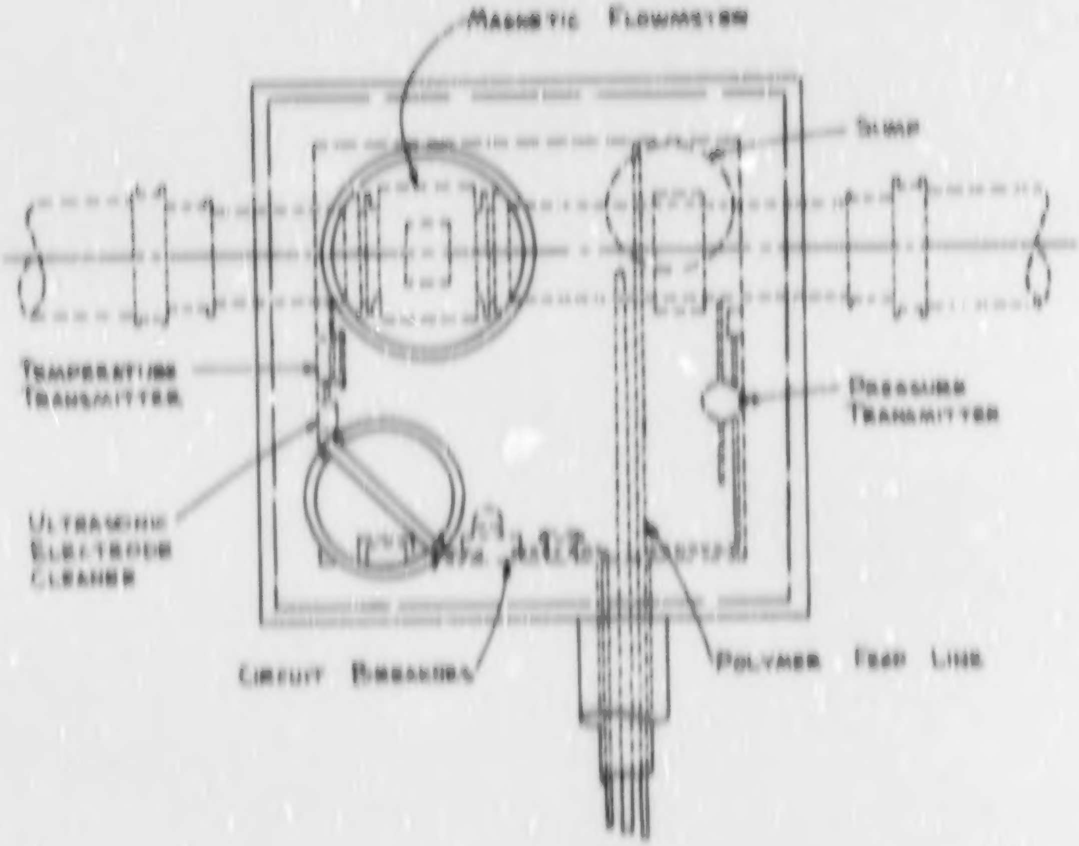

MAGNETIC FLOWMETER
SUMP
TEMPERATURE TRANSMITTER
PRESSURE TRANSMITTER
ULTRASONIC ELECTRODE CLEANER
CIRCUIT BREAKERS
POLYMER FEED LINE

FIGURE 40
PLAN OF INJECTION AND METERING VAULT
SHOWING THE LOCATION
OF MAJOR COMPONENTS

SECTION 16

ON-LINE OPERATION OF THE INJECTION FACILITY

GENERAL

Phase IV, the demonstration phase of the program, was designed to show that overflows in the study area could be controlled by the injection of friction-reducing chemicals into the sewer line and that the injection could be unattended (fully automated). In addition, it was intended that the data gathered during injection periods would extend the state of knowledge of the effect of polymer addition to larger pipes than had heretofore been utilized. Once the facility had been "de-bugged", it was extremely easy to demonstrate the control of overflows in both manual and automatic control modes. However, the generation of data which could be generalized was more difficult by orders of magnitude.

Earlier experiments in friction reduction were either performed under laboratory conditions or the subtle nuances of friction-reduction were ignored. Most of the field work performed falls in the second category with one notable exception; the work of Dr. R.H.J. Sellin in Wales. Dr. Sellin was fortunate enough to have a pressure wastewater line which was fed from a positive displacement pump, thereby making experiments at constant flow and constant concentration possible.

Friction-reduction data from earlier field tests had been reported in "percent flow increase" or "head reduction" with no correlation between the two parameters. The difference between these two parameters can be better understood by considering two experiments:

1. Constant Flow - Variable Head

2. Constant Head - Variable Flow

If one has a means whereby the flow through a pipeline can be kept constant, such as Dr. Sellin's pipe fed by a constant-displacement pump, then friction reduction affects only the *pressure* at the pump discharge. On the other hand, if a pipeline is fed from an overflowing head box, then friction reduction affects only the flow through the line. Unfortunately, most practical problems in dealing with sewage flow do not correspond to either of these examples, especially when one considers flow in gravity sewers.

Therefore, four types of experiments in friction reduction were designed for the demonstration phase of the program:

1. Manual control with fixed polymer feed rates to determine maximum head reduction as a function of polymer feed rate;
2. Automatic control with fixed polymer feed rates to determine the ability of holding a head in a band of values around a pre-selected set point;
3. Automatic control with the polymer feed rate proportional to the flow so that a constant polymer concentration can be maintained;
4. Automatic control with the polymer feed rate proportional to the critical sewer level to provide smoothing of the flow.

Experiments of all four types have been performed. The experiments are discussed in the following pages.

MANUAL CONTROL-FIXED FEED RATES

The first opportunity to check out the injection equipment occurred on October 16, 1973 at a time before the instrumentation had been de-bugged, so the data obtained was limited to level at the injection site. Figure 41 is a representation of that data. The test was started while the level in the sewer was rising. The injection was started at a rate of 1.46 pounds per minute and maintained until the level dropped to the top of the pipe. The injection was then stopped and the level returned to its previous high. The injection was re-started at a reduced rate of 1.1 pounds per minute. After the level dropped about 0.7 feet, the feed rate was reduced to 0.85 pounds per minute. The object of this reduction was to determine the minimum feed rate which would control the overflow. Note the reduced rate at which the level continued to drop.

One difficulty with a test at constant injection rate is caused by the reduced head; the effective concentration generally increases as the level drops. Although there is a concurrent phenomenon of increased flow initially, the flow system attempts to establish equilibrium at a lower head; this leads to reduced

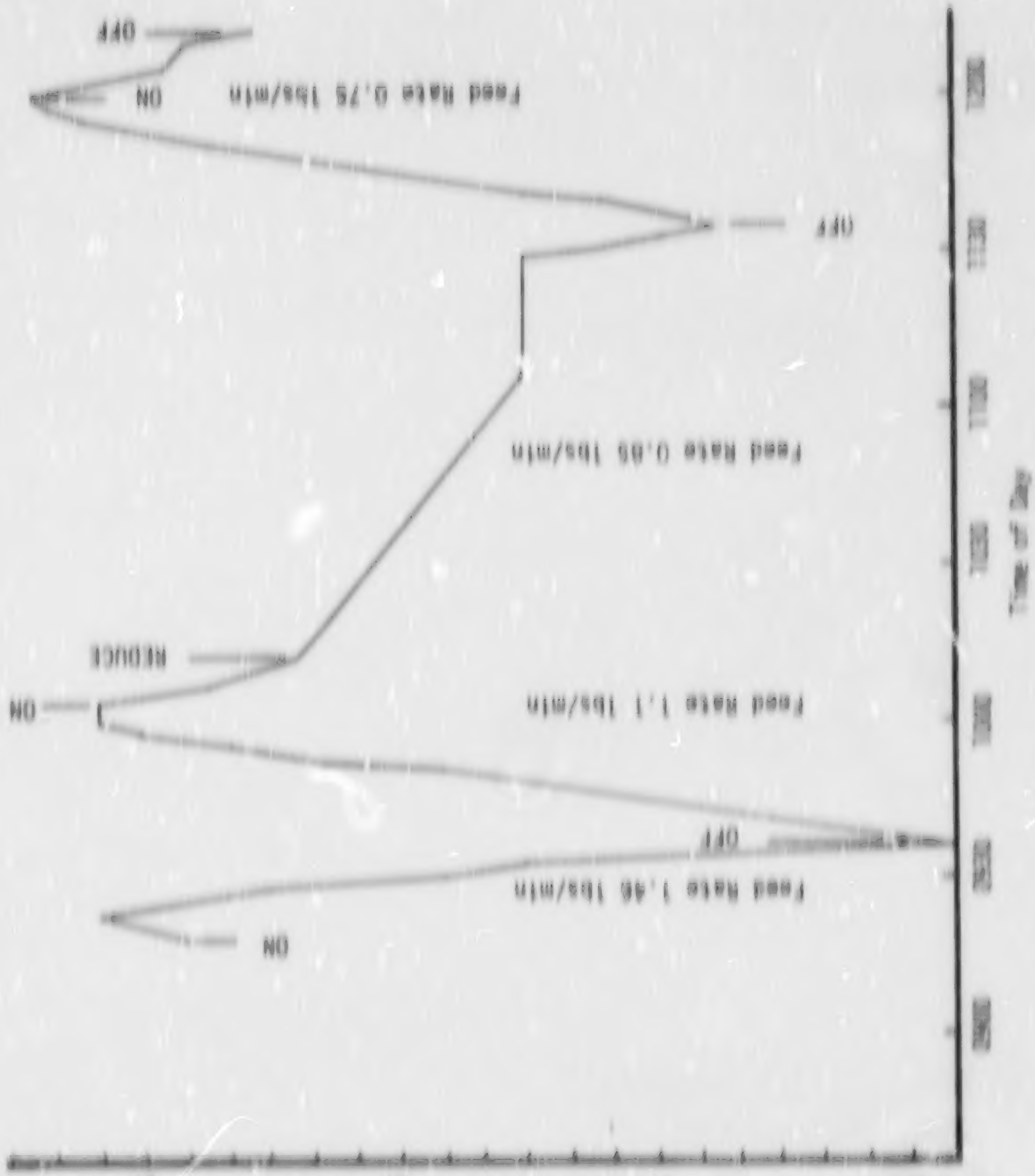


FIGURE 41. GRAPH OF MANUAL INJECTION TEST ON OCTOBER 16, 1973 AT VARIOUS FEED RATES (POLYOX WSR-301)

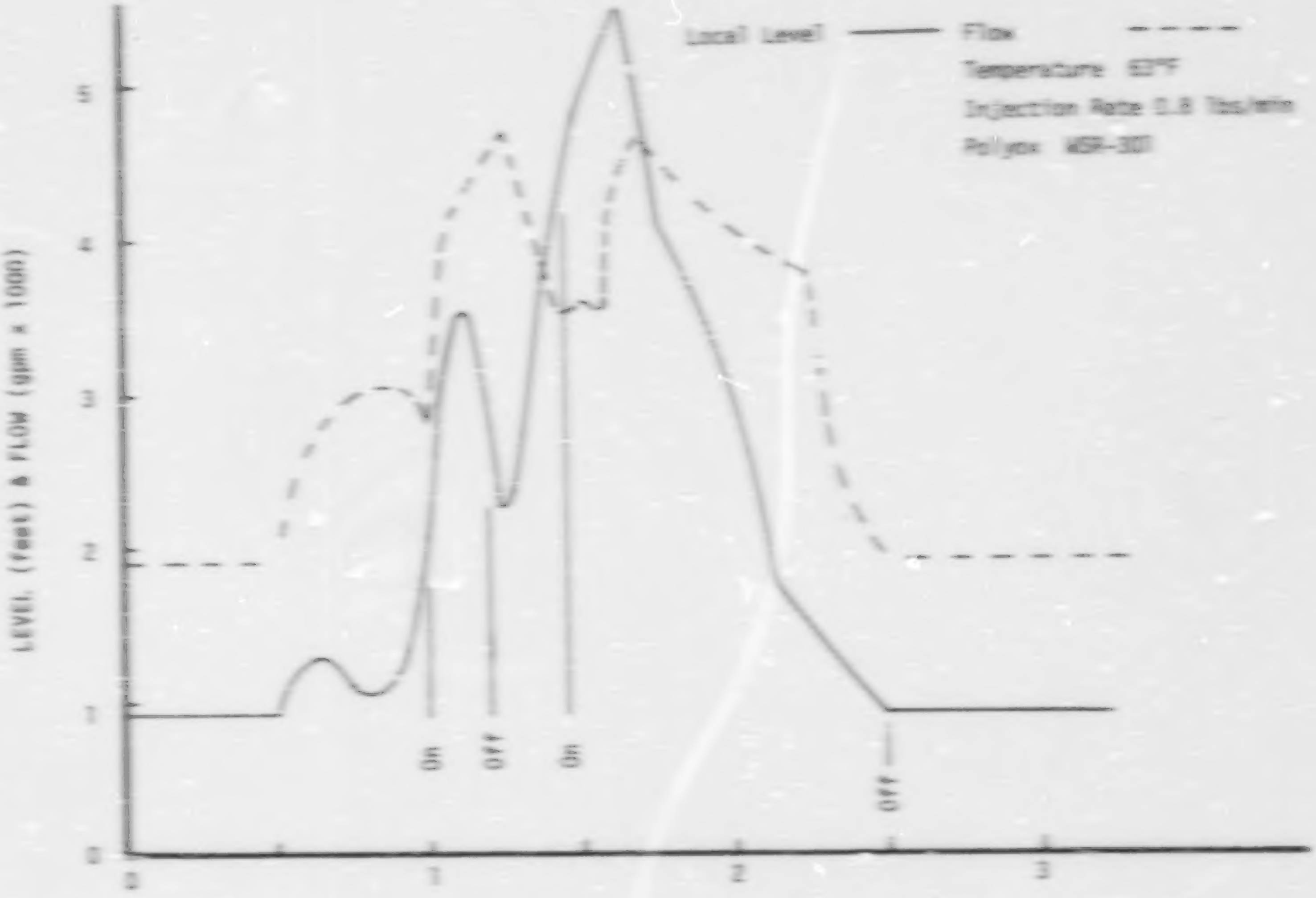


FIGURE 42. GRAPH OF FLOW AND LEVEL DURING DEMONSTRATION OF MANUAL INJECTION OF MARCH 27, 1974

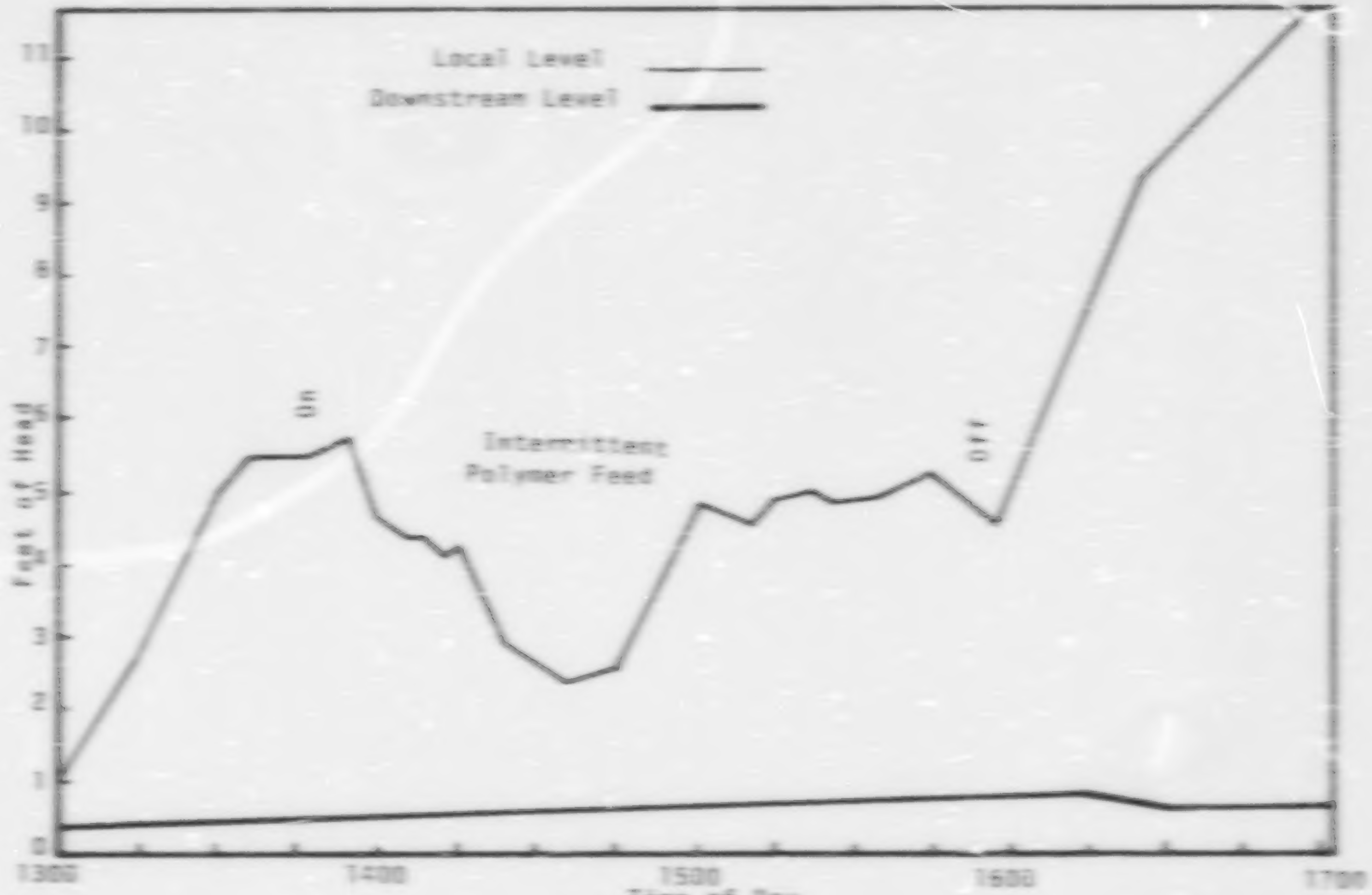


Figure 43. Graph of Manual Injection of May 5, 1974
Feed Rate Constant Because of Low Polymer Supply

flow which results in a higher concentration which results in greater friction reduction, et cetera. The foregoing is a simplified explanation of a very complex continuous function, but serves to illustrate the enormous difficulty one faces in analyzing large scale experimental data.

The second test was run as a demonstration on March 27, 1974. Since a suitable rainfall could not be scheduled for this demonstration, an inflow source was simulated by installing a "valve" in the place of a manhole cover approximately two miles upstream from the injection site and diverting the stream flow through this valve. The valve utilizes an 18 inch diameter "pillow packer" as the valve element.

Figure 42 is a graph of the demonstration test. The injection was manually controlled, with the injection rate set at 0.8 pounds per minute.

The third injection test performed under manual control began on May 5, 1974 as an automatic test. However, when the technician arrived at the station, he found that the polymer being dispensed was lumpy, causing the actual feed rate to vary. The lumps resulted from a failure of the dehumidifier which caused "crusting" of the surface layer. This layer was fed when the polymer supply was low. It was necessary to abort the injection after three hours because of difficulties in clearing the lumps. See figure 43.

AUTOMATIC CONTROL-FIXED POLYMER FEED RATE

With the control level set to start the injection at 45 inches, the graph of Figure 44 was produced on April 21, 1974. Under automatic control, the injection starts and stops at the preset level. A series of oscillations of level results from this type of control. Three on-off cycles appear on Figure 44. Inspection of the graph indicates the time lag caused by the build-up and purging of polymer over the 3,540 feet of sewer line immediately downstream.

Figure 45 is a graph of an injection at the same rate (0.8 pounds per minute) with the control level set at 30 inches. The level and flow graphs have similar characteristics as before, only at a lower level. There are four short injection cycles presented on the figure, with the last two of such short duration that the flow rate was not significantly affected.

AUTOMATIC CONTROL - POLYMER FEED RATE PROPORTIONAL TO FLOW

Because of repeated failures of the flowmeter only one successful test of constant polymer concentration has been performed.

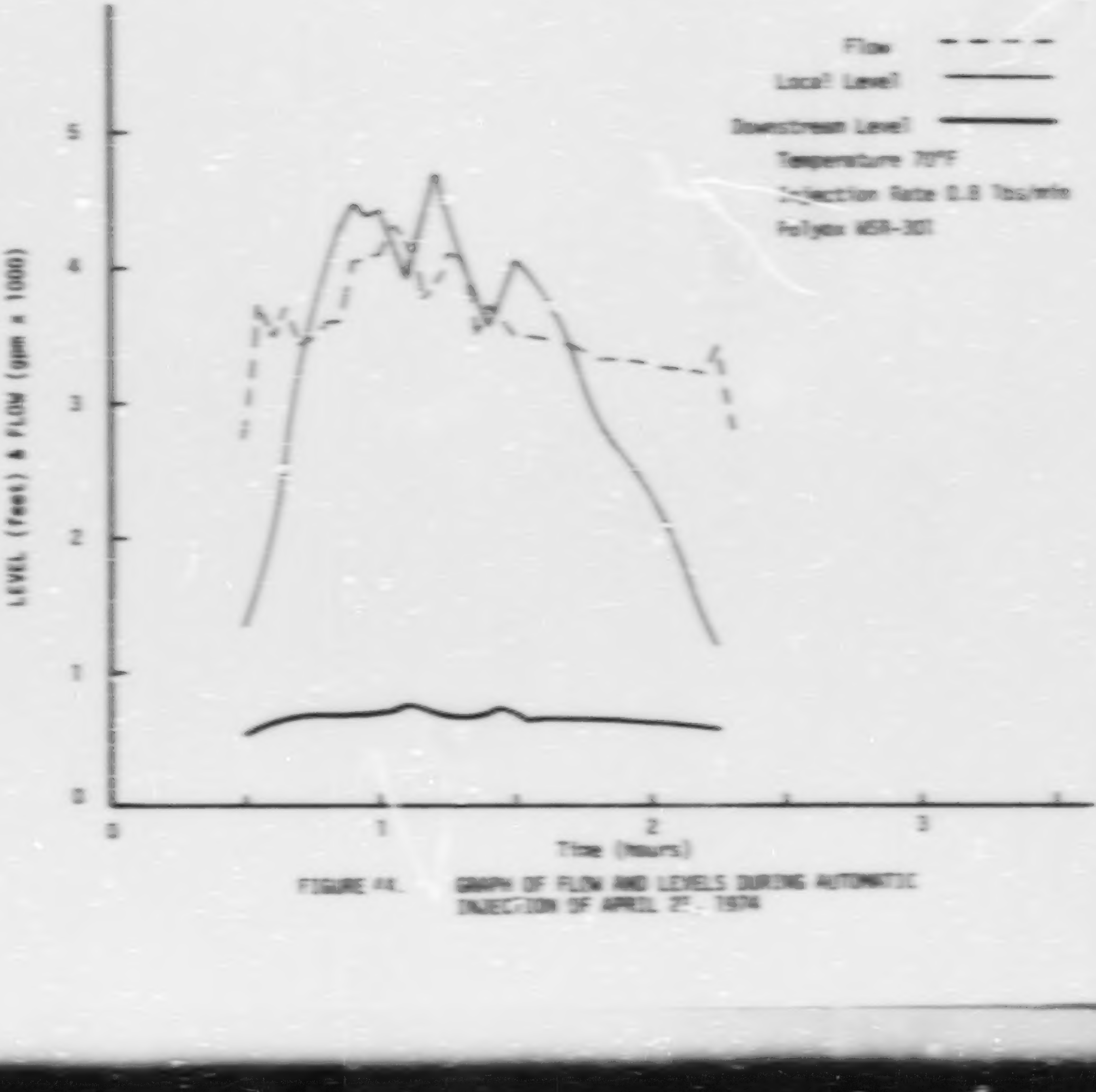


FIGURE 44. GRAPH OF FLOW AND LEVELS DURING AUTOMATIC INJECTION OF APRIL 27, 1974

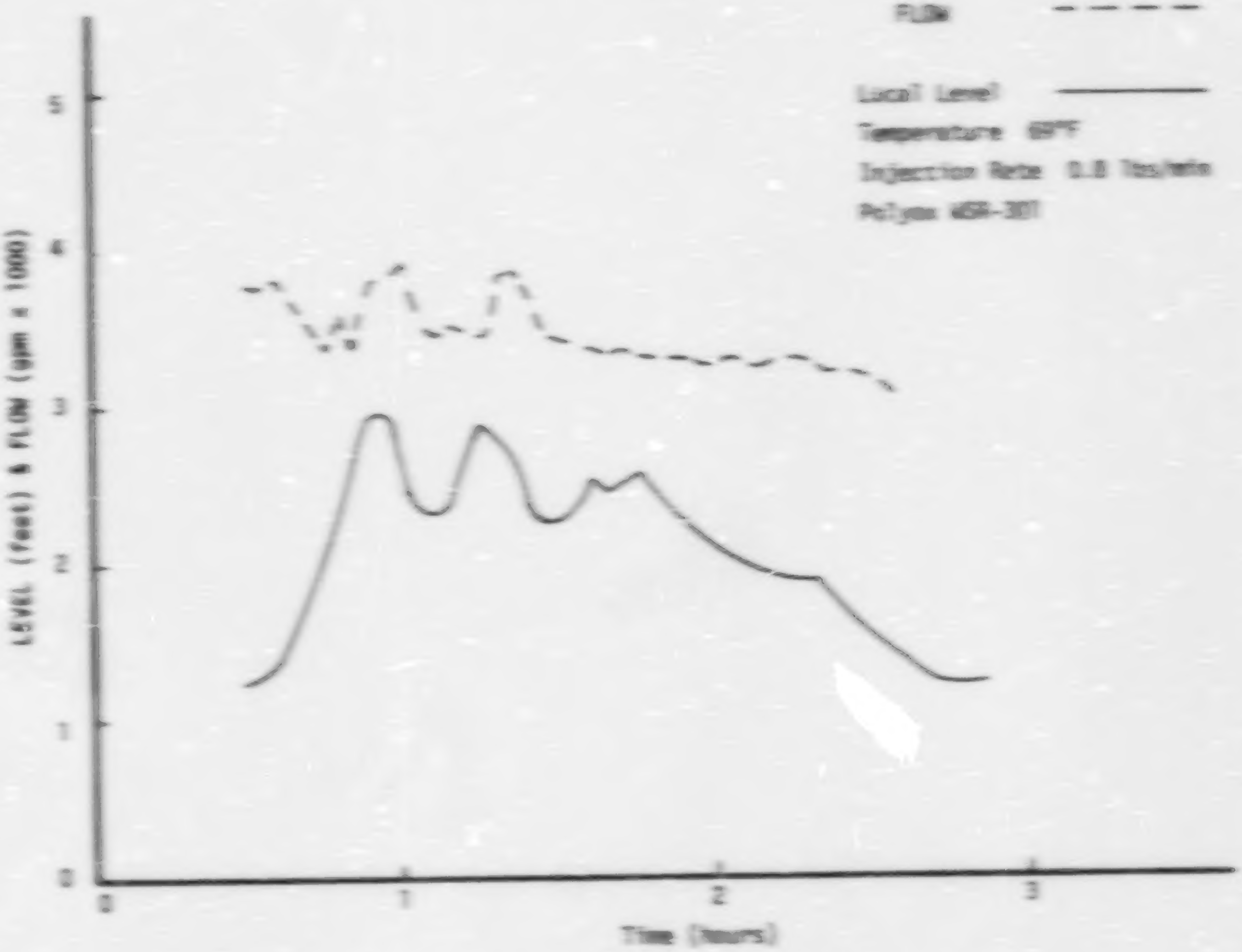


FIGURE 45. GRAPH OF FLOW AND LEVEL DURING AUTOMATIC INJECTION OF APRIL 22, 1974

This test is graphed in Figure 46, and occurred on May 1, 1974. The start-up level was set to 27 inches and the polymer feeder controls set to yield 30 parts per million concentration. Absent from Figure 46 are the rapidly changing levels which have characterized tests under other types of control. Rather, the flow graph showed variation as the injection mechanism executed two start-stop cycles.

AUTOMATIC CONTROL - POLYMER FEED RATE PROPORTIONAL TO LEVEL

Figure 47 illustrates the effect of allowing the magnitude of the "Local Level" govern the rate of polymer feed. This graph represents a test conducted on June 9, 1974. As the level in the sewer drops, the feed rate is decreased, causing a "rounding-out" of the level graph as it approaches some lower value asymtotically. Theoretically, there will be a gradual dampening of the curve variation when the feed rate is variable and level controlled. The level will even out at a particular level and maintain that level through control of the feed rate. If the level control uses a fixed feed rate, there will be a constant sawtooth pattern as the high head engages the feed mechanism; the head is reduced as a result of the polymer feed and a low head level disengages the feed mechanism. If the fixed feed rate is not enough to bring the head down to the cutoff point, the head will follow a pattern similar to that which would exist if no polymer were being added. The only difference would be that the head would be lower and the total flow would be higher.

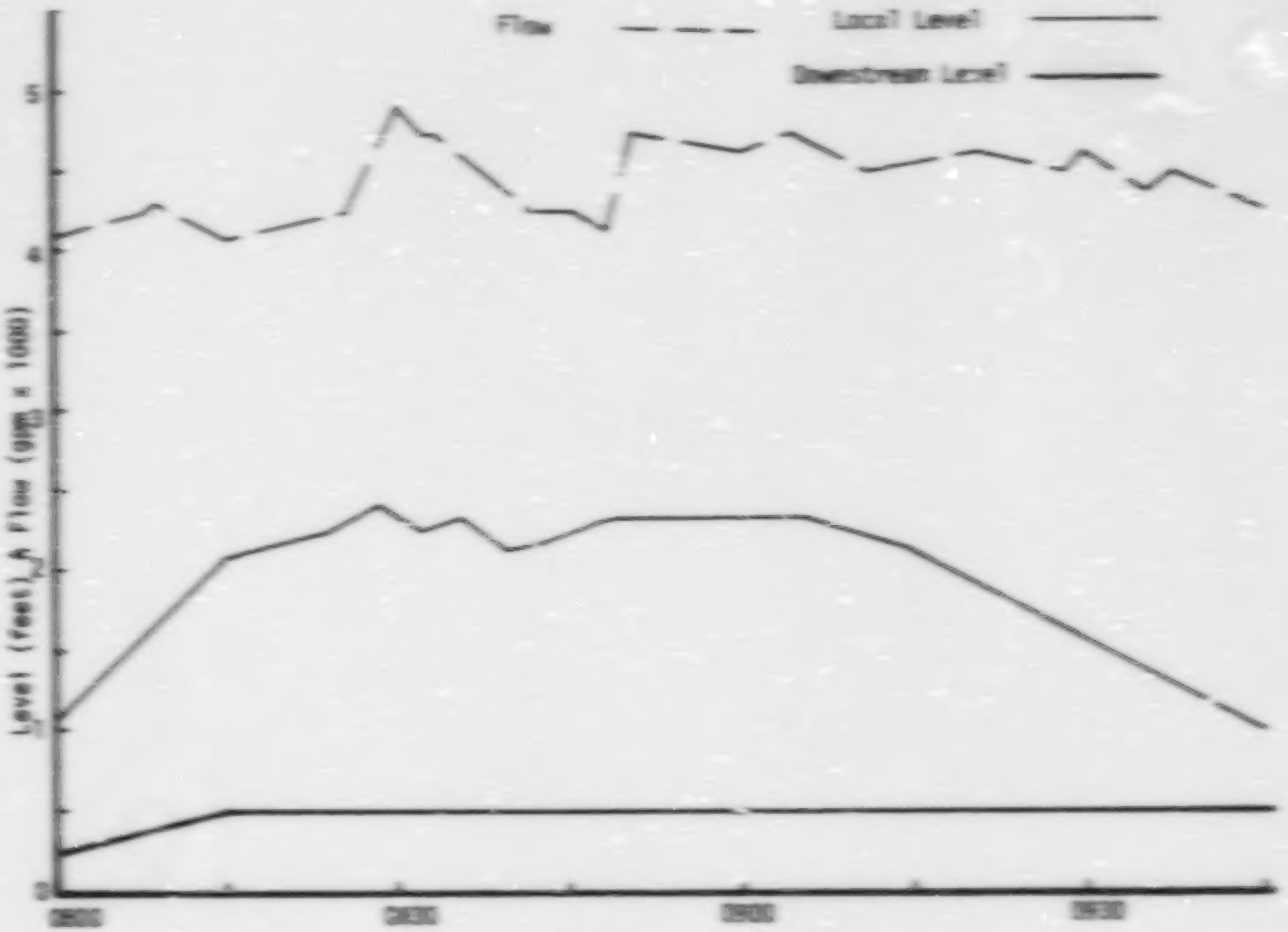


FIGURE 46. GRAPH OF AUTOMATIC INJECTION OF MAY 1, 1974
POLYMER FEED RATE PROPORTIONAL TO FLOW

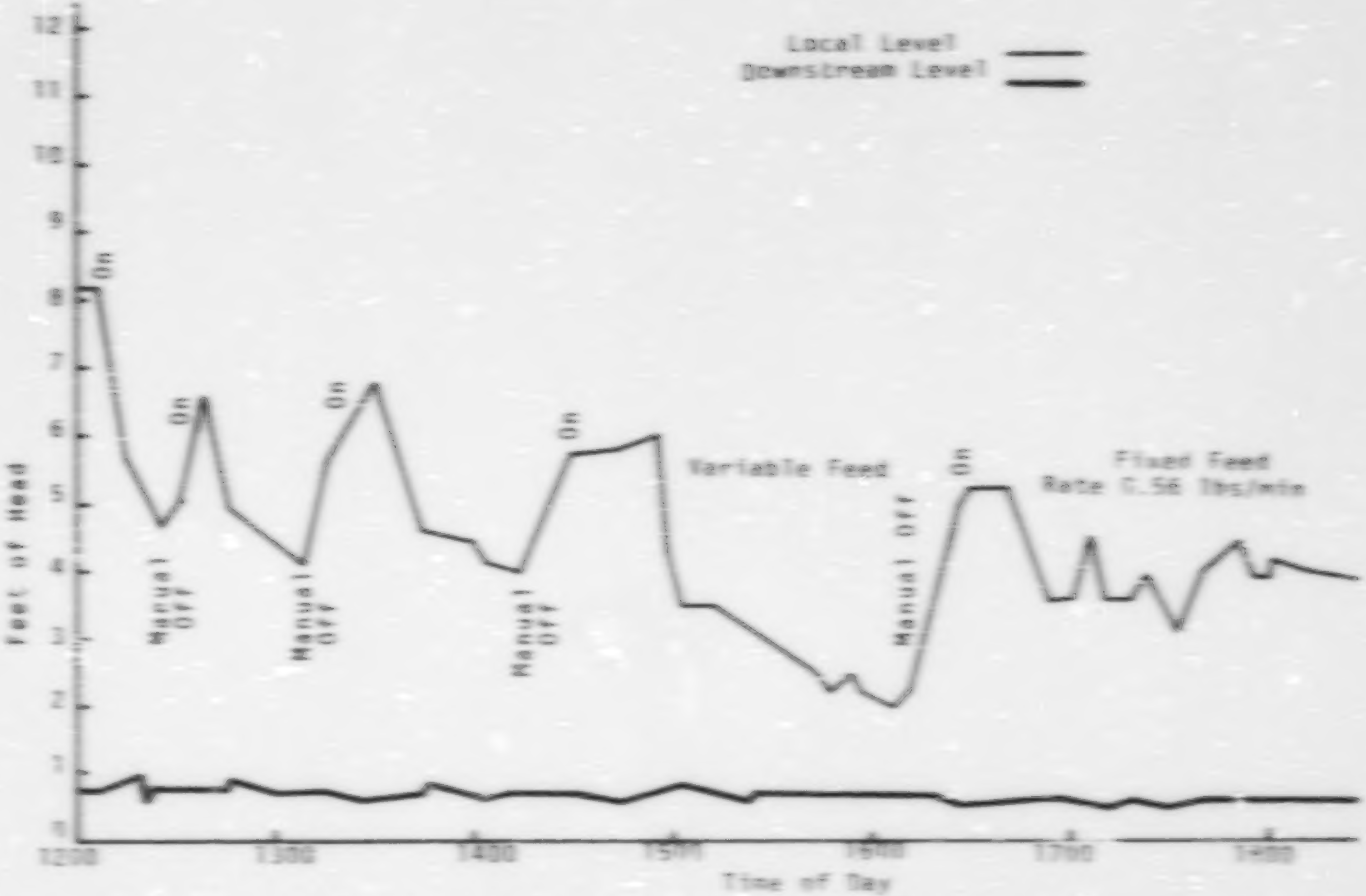


Figure 47 Graph of Downstream and Local Levels During Automatic Injection of June 9, 1974. Polymer Feed Proportional to Level

APPENDIX A

FRICTION REDUCING MATERIALS TESTED FOR CONFORMANCE TO PERFORMANCE SPECIFICATION

Product	Limiting Shear Stress* (psi)	Manufacturer
Percol 139	.011	Allied Colloids
Percol 155	.029	
Percol 351	.018	
RC-301	.011	American Cyanamid
RC-322	.011	
Polymer 1100	.018	Betz Chemical Co.
FR-X	.011	Calgon Chemical Co.
WCL 727	.011	
WCL 755	.011	
WT 3000	.011	
Separan AP30	.015	Dow Chemical Co.
Separan AP273	.022	
NGL 3958	.011	Stein, Hall and Co.
Polyox WSR 301	.011	Union Carbide
Polyox WSR 701	.018	
Polyox FRA	.022	

*Shear stress at which apparent degradation (or rupture) of the polymer chains occur.

APPENDIX B
CITY OF DALLAS
SPECIFICATION FOR
HIGH MOLECULAR-WEIGHT WATER SOLUBLE FRICTION-REDUCING ADDITIVES
No. PA-106-4061-70

I. PURPOSE

The purpose of this specification is to describe the performance characteristics of organic polymer materials for use as a viscoelastic fluid energy loss reducer in aqueous media.

II. GENERAL

A. These specifications are meant to include both natural and synthetic high-molecular weight materials such as polyacrylamides, polyethylene oxides and guar gum formulations.

B. The material may be supplied as a dry material, solution or stable suspension.

C. The material as supplied must not be highly hazardous in nature, i.e., it must not be toxic, highly corrosive, explosive or highly volatile.

D. The container in which the material is supplied should be sufficient to maintain the material in a usable state for a period of six months under reasonable storage conditions. Sacks or bags are not generally acceptable.

E. Each container should be clearly marked as to contents, precautions and storage instructions.

III. CHEMICAL AND PHYSICAL CHARACTERISTICS

The specifications shown in the following table are indicative of the materials commonly accepted under these specifications. Materials which depart from these guidelines will be evaluated on the basis of performance as a friction reducer.

PHYSICO-CHEMICAL PROPERTIES

Solubility in water	Readily soluble
Usable in pH range	4 - 11.5
Storage stability temperatures (for slurries or solutions)	35°F - 110°F
Molecular weight	500,000
Particle size	95% passing 30 mesh* or smaller 100% retained on 50 mesh*

*May be waived

IV. PERFORMANCE EVALUATION

A. Equipment

The equipment used in the evaluation test shall be a pressurized straight-tube flow apparatus illustrated by the attached drawing. It consists of a pressure vessel (A) fitted with a removable cover for filling and cleaning; a thermometer (B) mounted through the wall of (A) such that the temperature of the contents is determined; a tube (C) of stainless steel seamless tubing having an inside diameter of 0.18 inches and proportions as shown; pressure taps (D) and (E) assembled in such a manner to produce a minimum stream disturbance; laboratory-type differential pressure gauges (H) of ranges selected to provide a resolution of not more than 0.5-percent of the measured quantity; a throttling valve (F) to control the flow velocity; and apparatus (G) manual or automatic to determine flow rate gravimetrically or volumetrically.

B. Preparation of Test Material

A sample of the test material shall be dissolved in de-ionised water in the manner prescribed by the manufacturer in the proportions required to give a concentration of active friction reducer of up to 50 parts-per-million (ppm) by weight of water. This solution will be gently agitated for a sufficient length of time to insure a clear solution with no lumps or "fish-eyes." Materials shall be tested immediately after solution agitation. Made-up solutions will not be tested more than once or retained longer than 30 hours.

C. Method of Test

Two gallons of the solution prepared in (B) above shall be placed in the pressure vessel with valve (F) in closed position. With the pressure vessel open to atmospheric pressure, valve (F) will then be opened slightly until the tube (C) and fittings have been purged of air bubbles. Valve (F) will then be closed.

Static pressure is then built-up in the pressure vessel by means of an auxiliary pressure regulator and air or nitrogen source. The applied pressure should be adjusted between 10 - 160 psi.

When the above preparations have been completed, a "run" is made by opening valve (F) a preselected amount, measuring the steady-state flow and frictional pressure loss (as indicated by the differential pressure gauges).

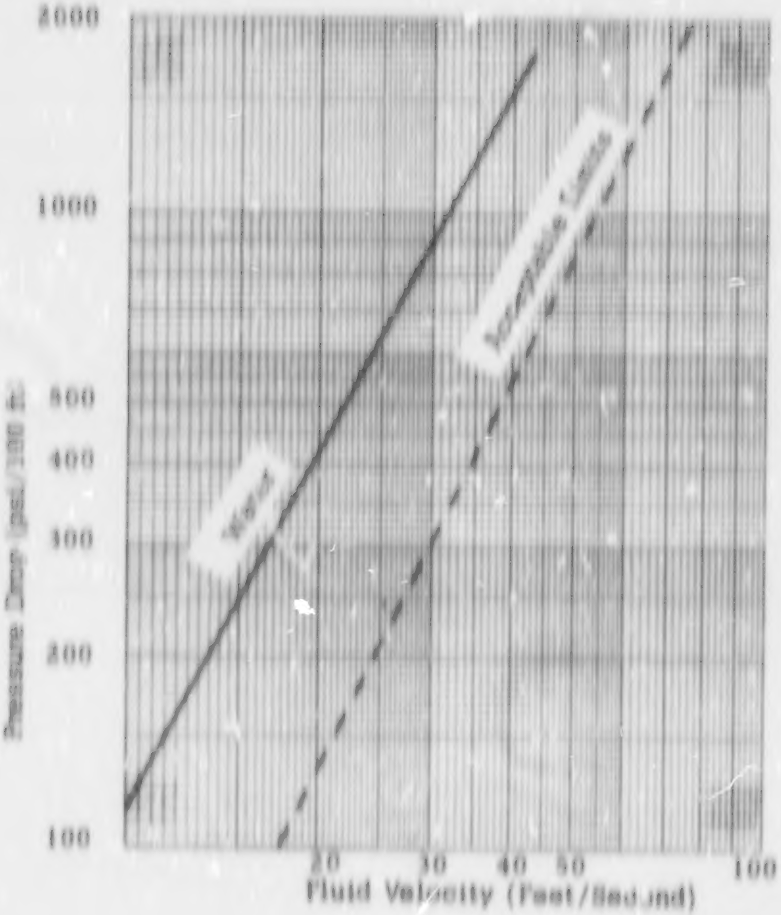
Tests should be performed at a minimum of three flow rates, with fresh solution used for each run.

D. Reporting of Results

Results should include the following information:

1. Material name or designation.
2. Material chemical genera (i.e., polyacrylamide).
3. Manufacturer.
4. Batch or lot number (if available).
5. Approximate molecular weight.
6. Remarks on solution appearance (i.e., clarity, etc.).
7. Temperature of material at the time of test.
8. A graph of pressure drop reduced to pressure loss per 100 feet of length and velocity in feet per second.

To qualify under the performance requirements of this specification, the graph results from item eight, above, should fall below and to the right of the dashed line in the figure below.


2000
1000
500
400
300
200
100
Pressure Drop (psi/100 ft)
Water
20
30
40
50
100
Fluid Velocity (Feet/Second)

APPENDIX C

SEWER MODELING PROGRAM

```
100 DIMENSION Q(3,23,3),AQ(3,23,3),PK(3,23,3),FL(3,23,3),TEL(3,23,3)
110 REAL LUF,INFIL,LOSS(3,23),INF(3,23,3),DELQ(3,23,3)
120 INTEGER ENT,SEG,ENTMAX(3),TT(3)
140 DO 5,I=1,3
150 DO 5,J=1,23
160 DO 5,K=1,3
170 TEL(I,J,K)=0;DELQ(I,J,K)=0;AQ(I,J,K)=0;FL(I,J,K)=0;Q(I,J,K)=0
180 5;PK(I,J,K)=1
190 $FILE DEFINE,LINES
200 READ(1)NLINES
210 DO 10,I=1,NLINES
220 READ(1)LIN,ENTMAX(LIN),TT(LIN)
230 10;CONTINUE
240 15;READ(1)LIN,ENT,SEG,AR,LUF,TEL(LIN,ENT,SEG),TPL,C,D,PL,FAC
250 D=D/12.
260 Q(LIN,ENT,SEG)=AR*LUF/720
270 AQ(LIN,ENT,SEG)=Q(LIN,ENT,SEG)
275 IF(D)999,17,16
280 16;PK(LIN,ENT,SEG)=(                  1/(((C*1.85)*(D*     ))
281 GOTO 19
282 17;PK(LIN,ENT,SEG)=1
290 19;INF(LIN,ENT,SEG)=TPL*FAC
310 IF(ENDFILE 1)15
320 READ(2)OUTFALL
330 20;READ(2)LIN,ENT,C,D,PL,TEL(LIN,ENT,3),LOSS(LIN,ENT)
340 D=D/12.
350 PK(LIN,ENT,3)=(          PL/(((C*1.85)*(D*     ))
360 IF(ENDFILE 2)20
370 P=1
380 30;I=NLINES
390 40;J=ENTMAX(I)
400 Q(I,J,3)=AQ(I,J,1)+AQ(I,J,2)
410 GOTO 60
420 50;Q(I,J,3)=AQ(I,J,1)+AQ(I,J,2)+Q(I,J+1,3)
430 60;J=J-1
440 IF(J)70,70,50
450 70;I=I-1
460 IF(I)100,100,75
470 75;IF(TT(I))100,80,90
480 90;J=ENTMAX(I)
490 Q(I,J,3)=AQ(I,J,1)+AQ(I,J,2)+Q(I+1,1,3)+Q(I+P,1,3)
500 J=J+1
510 IF(J)100,100,50
520 100:CONTINUE
530 DO 170,I=1,NLINES
540 J=1
550 IF(I-1)999,120,130
560 120:EL(I,1,3)=OUTFALL
570 GOTO 160
580 130:PP=(I-1)/2
590 IF(PP-INT(PP))999,140,150
600 140:PP=ENTMAX(I-1)
610 EL(I,1,3)=EL(I-1,PP,3)
620 GOTO 160
630 150:PP=ENTMAX(I-2)
640 EL(I,1,3)=EL(I-2,PP,3)
660 160:PP=ENTMAX(I)
670 DO 170,J=2,PP
680 F1=SIGN(FLOAT(C(I,J,3)))*.85,C(I,J,3))
700 161:EL(I,J,3)=EL(I,J-1,3)+C(I,J,3)*LOSS(I,J)
720 EL(I,J,3)=AMAX1(EL(I,J,3),TEL(I,J,3))
740 166:IF(PH(I,J,1)-1)167,168,167
750 167:EL(I,J,1)=EL(I,J,3)+SIGN(FLOAT(ABS(AC(I,J,1)))*.85),AC(I,J,1))
760 *PH(I,J,1)
765 EL(I,J,1)=AMAX1(EL(I,J,1),TEL(I,J,3)+1)
770 168:IF(PH(I,J,2)-1)169,170,169
780 169:EL(I,J,2)=EL(I,J,3)+SIGN(FLOAT(ABS(AC(I,J,2)))*.85),AC(I,J,2))
790 *PH(I,J,2)
795 EL(I,J,2)=AMAX1(EL(I,J,2),TEL(I,J,3)+1)
800 170:CONTINUE
810 IF(P/10-INT(P/10))999,171,174
820 171:PRINT 600
830 PRINT 610
840 DO 172,I=1,NLINES
850 PP=ENTMAX(I)
860 DO 172,J=1,PP
870 PRINT 620,I,J,EL(I,J,3),C(I,J,3)
880 DO 172,K=1,2
890 IF(PH(I,J,K)-1)STRETCH,172,STRETCH
900 STRETCH:PRINT 630,K,EL(I,J,K),AC(I,J,K),DEL(I,J,K),C(I,J,K)
910 172:CONTINUE
920 PRINT,"THE INFILTRATION RATE IS PRESENTLY",INFIL,"GALLONS/MIN/FT"
930 PRINT,"DO YOU WISH TO CONTINUE THE PROBLEM (YES OR NO)?"
940 INPUT,IA
950 IF(IA="NO")173,999,173
960 173:PRINT,"TYPE A VALUE FOR THE INFILTRATION RATE INCREMENT"
970 PRINT,"(DECREMENT)AFTER THE QUESTION MARK."
980 INPUT,F
985 IF(F)174,175,174
990 174:INFIL=INFIL+F
1000 DO 177,I=1,NLINES
1010 PP=ENTMAX(I)
1020 DO 177,J=1,PP
```

```
1030 DO 177,K=1,P
1040 Q(I,J,K)=C(I,J,K)+INF(I,J,K)*P
1050 177:AQ(I,J,K)=Q(I,J,K)
1060 GOTO 210
1070 179:DO 200,I=1,NLINE1
1080 PP=ENTMAX(I)
1100 DO 200,K=1,P
1110 IF(PM(I,J,K)-1)STAR,200,STAR
1120 STAR:CH=TEL(I,J,K)-EL(I,J,K)
1130 IF(CH)191,200,180
1140 180:AQ(I,J,K)=AQ(I,J,K)+0.5*ABS(AQ(I,J,K))
1145 IF(AQ(I,J,K)-Q(I,J,K))200,200,185
1150 185:AQ(I,J,K)=Q(I,J,K)
1160 GOTO 200
1180 191:AQ(I,J,K)=AQ(I,J,K)-0.5*ABS(AQ(I,J,K))
1185 AQ(I,J,K)=AMAX1(AQ(I,J,K),Q(I,J+1,3))
1190 IF(AQ(I,J,K))200,192,200
1195 192:IF(Q(I,J,K))200,195,200
1210 195:AQ(I,J,K)=-10.
1230 200:DELQ(I,J,K)=Q(I,J,K)-AQ(I,J,K)
1240 210:P=P+1
1250 GOTO 30
1260 A00:FORMAT(2X,4HLINE,2X,4HNODE,2X,4HAREA,7X,5HELEV.,6X,4HFLOW,
1270 *7X,8HOVERFLOW,7X,9HAREA FLOW)
1280 A10:FORMAT(24X,3HFT.,8X,3HCFS,10X,3HCFS,10X,3HCFS)
1290 A20:FORMAT(I6,I6,11X,F7.2,3X,F9.2,3H***)
1300 A30:FORMAT(12X,I6,5X,F7.2,3X,F9.2,3X,F9.2,3X,F9.2)
1310 999 STOP
```

APPENDIX D

BACHMAN CREEK INPUT DATA

INPUT DATA FOR BACHMAN CREEK COMPUTER MODEL

Line	Entry	1-N-W 2-S-E Serial	Area in Acres	Land Use Factor	Overflow Elevation (Feet)	Total Pipe Length (Feet)	C	Pipe Dia. (Inches)	Feet Pipe Length (Feet)	Factor
1	1	----	----	----	----	----	----	----	----	----
1	2	1	----	----	427.5	----	100	----	----	----
1	3	2	----	----	448.5	----	970	----	----	----
1	4	1	----	----	447.0	----	100	----	----	----
1	5	2	----	----	446.5	----	100	----	----	----
1	6	2	17.0	1600	455.0	2340.0	100	8	320.0	1.
1	7	2	31.0	1600	444.0	4070.0	100	8	150.0	1.
1	8	1	5.0	550	444.0	6520.0	100	15	267.0	1.
1	9	1	7.0	1600	444.4	7830.0	100	18	175.0	1.
1	10	2	41.0	950	490.0	7400.0	100	8	1000.0	1.
1	11	1	11.3	1600	446.0	1150.0	100	8	470.0	1.
1	11	2	1222.0	950	500.0	5807.0	100	10	1700.0	1.
1	12	2	51.6	950	500.0	5400.0	100	8	1725.0	1.
1	13	2	89.0	950	471.94	7800.0	100	8	1200.0	1.
1	14	1	134.0	950	450.0	1392.5	100	10	2875.0	1.
1	14	2	59.0	550	474.0	5124.0	100	8	3370.0	1.
1	15	1	1.0	250	471.25	200.0	100	6	200.0	1.
1	16	2	2.0	500	471.5	1300.0	100	8	306.0	1.
1	17	2	1.0	250	462.0	2890.0	100	6	200.0	1.
1	18	1	79.0	550	491.0	7100.0	100	8	1050.0	1.
1	18	2	189.0	550	475.0	16325.0	100	15	450.0	1.
1	19	1	13.0	550	495.0	1100.0	100	8	1900.0	1.
1	20	2	579.0	550	485.0	60913.0	100	18	250.0	1.
1	21	1	47.0	550	497.0	4905.0	100	8	330.0	1.
1	21	2	307.0	550	487.4	28940.0	100	12	400.0	1.
1	22	1	60.0	550	487.5	9675.0	130	8	675.0	1.

(Continued)

Line	Entry	1-S-W 2-S-E Serial	Area in Acres	Land Use Factor	Overflow Elevation (Feet)	Trial Pipe Length (Feet)	C	Pipe Dia. (Inches)	Feed Pipe Length (Feet)	Factor
2	2	2	41.5	550	515.0	4040.0	100	8	2600.0	1.
2	3	2	75.0	550	536.0	4275.0	100	10	515.0	1.
2	4	1	----	----	513.6	----	120	12	3.0	----
2	5	1	254.0	550	534.5	24275.0	100	15	1700.0	1.
2	5	2	46.0	550	545.0	3725.0	100	8	425.0	1.
2	6	1	47.0	550	553.0	3250.0	100	8	550.0	1.
2	7	2	15.0	550	585.0	1500.0	100	8	1200.0	1.
2	9	2	28.0	550	585.0	2800.0	100	8	10000.0	1.
2	10	2	32.0	550	587.0	3200.0	100	8	10000.0	1.
2	11	2	32.0	550	588.0	3200.0	100	8	10000.0	1.
2	12	2	29.0	550	590.0	3600.0	100	8	10000.0	1.
2	13	2	30.0	550	591.0	3000.0	100	8	10000.0	1.
2	14	2	30.0	550	594.0	3000.0	100	8	10000.0	1.
2	15	2	30.0	550	594.0	3600.0	100	8	10000.0	1.
2	16	2	39.0	550	599.0	3905.0	100	8	10000.0	1.
2	17	1	----	----	588.0	----	120	12	3.0	1.
2	17	2	38.0	550	596.0	3800.0	100	10	10000.0	1.
2	18	2	40.5	550	599.0	4000.0	100	10	10000.0	1.
2	19	1	----	----	589.0	----	120	12	50.0	0
2	19	2	41.0	550	597.0	4100.0	100	10	1000.0	1.
2	20	1	114.0	550	596.0	15200.0	100	10	1700.0	1.
2	20	2	95.0	550	602.0	9500.0	100	8	700.0	1.
2	21	1	1779.0	300	700.0	177900.0	100	30	100.0	1.
3	2	2	----	----	477.0	----	60	4	90.0	1.
3	3	1	140.0	550	500.0	7875.0	100	12	2200.0	1.
3	4	1	----	----	489.15	----	60	6	20.0	----
3	5	1	----	----	487.0	----	60	4	15.0	----

(Continued)

Line	Entry	1-N-W 2-S-E Serial	Area in Acres	Land Use Factor	Overflow Elevation (Feet)	Total Pipe Length (Feet)	C	Pipe Dia. (Inches)	Feet Pipe Length (Feet)	Factor
3	6	1	----	----	488.0	----	40	4	15.0	----
3	7	1	----	----	490.0	----	60	4	15.0	----
3	8	1	----	----	493.1	----	40	4	20.0	----
3	9	1	212.0	550	515.0	22950.0	100	10	400.0	1.
3	10	2	14.5	550	520.0	2050.0	90	6	300.0	1.
3	11	2	142.0	550	520.0	11950.0	100	10	20.0	1.
3	12	1	128.0	550	532.0	11575.0	100	16	1125.0	1.
3	13	2	131.0	550	547.0	9125.0	100	18	800.0	1.
3	14	2	112.0	550	550.0	7425.0	100	20	40.0	1.
3	17	1	1256.0	550	600.0	115600.0	100	18	1000.0	1.

(Continued)

Line No.	Entry No.	Station No.	Pipe Diameter (Inches)	Pipe Length (Feet)	Invert. Elevation (Feet Above MSL)	Minor Head Loss (Feet)
1	1	0 + 50	----	----	418.00	----
1	2	5 + 72.28	30	572.28	425.26	.1
1	3	15 + 17.75	32	945.47	424.04	.325
1	4 +	16 + 75.00	30	157.25	425.00	.2
1	5	23 + 79.00	36	704.00	426.60	.15
1	6	33 + 25.00	36	946.00	427.80	.1
1	7	47 + 30.00	36	405.00	429.89	.1
1	8	82 + 45.00	36	3525.00	434.90	.3
1	9	87 + 00.00	36	455.00	435.50	.8
1	10	106 + 50.00	36	1950.00	438.18	.1
1	11	116 + 67.32	36	1170.32	439.60	.1
1	12	121 + 23.00	33	456.68	440.24	.1
1	13	128 + 10.83	36	687.83	441.20	.1
1	14 +	150 + 32.49	36	2054.26	446.89	.95
1	15 ⊕	160 + 70.00	24	1037.91	452.00	.2
1	16 ⊕	164 + 33.00	24	363.00	453.80	.1
1	17 ⊕	166 + 21.58	24	188.58	454.84	.1
1	18	178 + 66.0	24	344.42	457.00	.2
1	19	181 + 72.14	24	1106.14	466.10	.27
1	20	186 + 68.76	24	496.62	466.14	.2
1	21 +	198 + 78.00	24	1209.24	470.37	.47
1	22	206 + 25.04	24	747.04	472.96	.07
1	23 +	211 + 90.00	24	564.96	475.24	.32

- Overflow + Change in Pipe Size ⊕ Instrument Installation

(Continued)

Line No.	Entry No.	Station No.	Pipe Diameter (Inches)	Pipe Length (Feet)	Invert. Elevation (Feet Above MSL)	Minor Head Loss (Feet)
2	2 *	221 + 26.26	18	936.26	481.78	.58
Browning	3	233 + 54.97	15	1226.71	496.58	.3
Branch	4 *	245 + 77.38	15	1222.41	506.36	.1
2	5 *	259 + 36.67	15	1349.29	516.94	.58
2	6	262 + 19.4	15	282.73	538.00	.2
2	7	293 + 34.65	15	3115.25	570.94	.6
2	8	297 + 24.62	15	389.97	571.52	.2
2	9 +	309 + 73.77	15	1249.15	573.51	.4
2	10	313 + 41.78	12	368.01	575.99	.1
2	11	315 + 64.55	12	222.77	576.77	.1
2	12	317 + 06.20	12	141.65	577.52	.1
2	13	320 + 67.84	12	361.64	578.14	.1
2	14	324 + 34.75	12	364.51	578.76	.1
2	15	328 + 08.10	12	371.85	579.39	.1
2	16	332 + 57.37	12	449.27	580.19	.1
2	17 * *	340 + 50.08	12	792.61	581.67	.1
2	18	346 + 64.38	10	614.28	585.82	.1
2	19 *	349 + 20.00	10	275.98	587.48	.3
2	20	355 + 40.38	10	640.10	591.58	.1
2	21	OBS	10	1000.07	621.05	.1
3	—	—	—	—	—	—
Bachman	2 *	4 + 00.00	18	400.00	476.95	.01
Branch	3	7 + 48.80	15	348.80	478.52	.15
3	4 *	9 + 25.00	18	172.80	479.15	.1

+ Overflow * Change in Pipe Size ⊕ Instrument Installation

(Continued)

Line No.	Entry No.	Station No.	Pipe Diameter (Inches)	Pipe Length (Feet)	Invert. Elevation (Feet Above MSL)	Minor Head Loss (Feet)
5	5 ◆	14 + 77.50	18	557.50	482.90	.17
5	6 ◆	16 + 74.00	18	196.50	483.80	.6
5	7 ◆	17 + 86.00	18	112.00	485.08	.01
5	8 + ⊖	29 + 35.00	18	921.00	489.15	.13
5	9 ⊖	35 + 40.50	18	605.00	492.17	.36
5	10 ⊖	35 + 80.05	18	40.00	492.28	.1
6	11	62 + 41.50	18	2661.50	505.60	.12
→5M	12	75 + 00.00	18	1258.97	513.66	.10
5M	13	79 + 66.30	18	466.30	517.12	.16
5	14	97 + 50.00	18	1783.70	527.75	.17
5	15	CBB	18	1000.00	550.00	.1

→ Overflow ◆ Change in Pipe Size ⊖ Instrument Installation

APPENDIX E
COMPUTER OUTPUT FROM MODELING PROGRAM

RUN #1

```
LINE   NODE   AREA         ELEV.         FLOW          OVERFLOW          AREA FLOW
                            FT.           GPM             GPM               GPM
  1      1                417.00       3567.60***
  1      2                420.28       3567.60***
  1      3                424.08       3567.60***
  1      4                425.00       3567.60***
  1      5                426.60       3567.60***
  1      6                427.80       3567.60***
                2         428.50         27.00            .00             27.00
  1      7                429.83       3540.60***
                2         430.49         49.80            .00             49.80
  1      8                434.90       3490.80***
                1         433.90          2.75            .00              2.75
  1      9                435.50       3488.05***
                1         436.50         11.20            .00             11.20
  1     10                438.10       3476.85***
                2         439.10         38.95            .00             38.95
  1     11                439.60       3437.90***
                1         440.60         18.08            .00             18.08
                2         440.60        115.90            .00            115.90
  1     12                440.20       3303.92***
                2         441.24         49.52            .00             49.52
  1     13                441.30       3254.40***
                2         442.20         84.05            .00             84.05
  1     14                446.87       3170.35***
                1         447.09        127.30            .00            127.30
                2         447.49         32.45            .00             32.45
  1     15                450.00       3010.60***
                1         453.08           .25            .00               .25
  1     16                452.80       3010.35***
                2         454.00          1.00            .00              1.00
  1     17                454.84       3009.35***
                2         455.84           .25            .00               .25
  1     18                457.08       3009.10***
                1         458.[illegible]         43.45            .00             43.45
                2         459.06        103.95            .00            103.95
  1     19                466.10       2861.70***
                1         467.10          7.15            .00              7.15
  1     20                466.92       2854.55***
```

LINE	NODE	AREA	ELEV. FT.	FLOW GPM	OVERFLOW GPM	AREA FLOW GPM
		2	467.14	318.45	.00	318.45
1	21		470.37	1536.10***		
		1	471.37	25.85	.00	25.85
		2	471.37	168.85	.00	168.85
1	22		472.99	2341.40***		
		1	473.99	33.00	.00	33.00
1	23		475.24	2308.40***		
2	1		475.24	1188.87***		
2	2		481.78	1188.87***		
		2	482.78	22.82	.00	22.82
2	3		496.58	1166.05***		
		2	497.58	41.25	.00	41.25
2	4		506.36	1124.80***		
		1	507.36	.00	.00	.00
2	5		516.84	1124.80***		
		1	517.84	139.70	.00	139.70
		2	517.84	25.30	.00	25.30
2	6		538.00	959.80***		
		1	539.00	25.85	.00	25.85
2	7		570.94	933.95***		
		2	571.94	8.25	.00	8.25
2	8		571.65	925.70***		
2	9		573.68	925.70***		
		2	574.53	15.40	.00	15.40
2	10		575.59	910.30***		
		2	576.59	17.60	.00	17.60
2	11		576.77	892.70***		
		2	577.77	17.60	.00	17.60
2	12		577.52	875.10***		
		2	578.52	15.95	.00	15.95
2	13		578.76	859.15***		
		2	579.18	16.50	.00	16.50
2	14		579.96	842.65***		
		2	579.97	16.50	.00	16.50
2	15		581.15	826.15***		
		2	581.16	16.50	.00	16.50
2	16		582.51	809.65***		
		2	582.53	21.45	.00	21.45
2	17		584.72	788.20***		
		1	584.78	.00	.00	.00
		2	584.73	20.90	.00	20.90
2	18		588.39	767.30***		
		2	588.39	22.00	.00	22.00
2	19		589.98	745.30***		
		1	589.98	.00	.00	.00
		2	589.99	22.55	.00	22.55
2	20		593.41	722.75***		
		1	593.67	108.30	.00	108.30
		2	593.58	40.75	.00	40.75
2	21		601.00	573.70***		

```
LINE   NODE   AREA  ELEV.         FLOW              OVERFLOW  AREA FLOW
                     FT.           GPM                GPM       GPM
                 1  602.00        535.70              .00      535.70
  3      1          475.24       1119.52***
  3      2          476.95       1119.52***
                 0  477.95          .00               .00         .00
  3      3          478.52       1119.52***
                 1  479.52         77.00              .00       77.00
  3      4          479.15       1042.52***
                 1  480.15          .00               .00         .00
  3      5          482.90       1042.52***
                 1  483.90          .00               .00         .00
  3      6          483.80       1042.52***
                 1  484.80          .00               .00         .00
  3      7          485.00       1042.52***
                 1  486.00          .00               .00         .00
  3      8          487.15       1042.52***
                 1  490.15          .00               .00         .00
  3      9          492.17       1042.52***
                 1  493.17        116.60              .00      116.60
  3     10          492.29        925.92***
                 2  493.29          7.97              .00        7.97
  3     11          505.60        917.95***
                 0  506.60         78.10              .00       78.10
  3     12          513.86        839.85***
                 1  514.86         70.40              .00       70.40
  3     13          517.12        769.45***
                 2  518.12         72.05              .00       72.05
  3     14          527.75        697.40***
                 2  528.75         61.60              .00       61.60
  3     15          550.00        635.80***
                 1  551.00        635.80              .00      635.80
 THE INFILTRATION RATE IS PRESENTLY .00  GALLONS/MIN/FT OF LATERAL
```

RUN # 2

```
LINE   NODE   AREA        ELEV.        FLOW          OVERFLOW   AREA FLOW
                           FT.          GPM            GPM        GPM
   1      1               419.00     7281.85***
   1      2               422.57     7281.85***
   1      3               424.04     7281.85***
   1      4               425.00     7281.85***
   1      5               426.60     7281.85***
   1      6               427.80     7281.85***
                 2        428.80       46.00            .00        46.00
   1      7               429.89     7235.85***
                 2        430.89       82.16            .00        82.16
   1      8               434.90     7153.69***
                 1        435.90       54.91            .00        54.91
   1      9               435.50     7098.78***
                 1        436.50       73.84            .00        73.84
   1     10               438.18     7024.94***
                 2        439.18       98.15            .00        98.15
   1     11               439.60     6926.79***
                 1        440.60       27.28            .00        27.28
                 2        440.60      162.30            .00       162.30
   1     12               440.24     6737.21***
                 2        441.24       92.22            .00        92.22
   1     13               441.80     6644.99***
                 2        442.20      146.95            .00       146.95
   1     14               446.89     6498.04***
                 1        448.81      238.70            .00       238.70
                 2        447.49       73.44            .00        73.44
   1     15               452.51     6185.90***
                 1        453.08        1.85            .00         1.85
   1     16               454.51     6184.05***
                 2        454.80       11.40            .00        11.40
   1     17               455.59     6172.65***
                 2        455.84       16.25            .00        16.25
   1     18               457.57     6156.40***
                 1        458.06      100.25            .00       100.25
                 2        458.06      250.55            .00       250.55
   1     19               466.10     5805.60***
                 1        467.10       15.95            .00        15.95
   1     20               467.60     5789.65***
                 2        468.71      805.75            .00       805.75
   1     21               473.30     4983.89***
                 1        473.36       65.09            .00        65.09
                 2        473.68      400.37            .00       400.37
   1     22               475.65     4518.43***
                 1        475.81       78.40            .00        78.40
   1     23               477.57     4440.03***
   2      1               477.57     1830.11***
   2      2               481.78     1830.11***
                 2        482.78       55.30            .00        55.30
   2      3               496.58     1774.80***
                 2        497.18       90.65            .00        90.65
```

```
LINE NODE    AREA      ELEV.        FLOW       OVERFLOW AREA FLOW
                        FT.          CFM         CFM
  2     4             506.36     1684.15***
                1     507.36          .00         .00         .00
  2     5             516.82     1684.15***
                1     517.82       323.90         .00      323.90
                2     517.84        55.10         .00       55.10
  2     6             538.00     1305.15***
                1     539.00        51.45         .00       51.45
  2     7             570.94     1253.70***
                2     571.94        30.05         .00       30.05
  2     8             571.39     1223.65***
  2     9             575.13     1223.65***
                2     575.19        38.00         .00       38.00
  2    10             577.38     1185.65***
                2     577.40        43.20         .00       43.20
  2    11             578.60     1142.45***
                2     578.62        43.20         .00       43.20
  2    12             579.20     1099.25***
                2     579.47        39.95         .00       39.95
  2    13             581.19     1059.30***
                2     581.25        40.50         .00       40.50
  2    14             582.84     1018.80***
                2     582.91        40.50         .00       40.50
  2    15             584.43      978.30***
                2     584.50        40.50         .00       40.50
  2    16             586.19      937.80***
                2     586.30        52.65         .00       52.65
  2    17             588.91      885.15***
                1     588.91       -33.75       33.75         .00
                2     588.95        51.30         .00       51.30
  2    18             593.48      867.60***
                2     593.49        30.37       23.63       54.00
  2    19             595.39      837.23***
                1     595.39       -33.75       33.75         .00
                2     595.39        10.38       44.97       55.35
  2    20             600.08      860.60***
                1     600.08        14.37      215.53      229.90
                2     600.10        27.89      120.86      148.75
  2    21             606.71      818.34***
                1     607.36       818.34         .00      818.34
  3     1             477.57     2609.92***
  3     2             479.14     2609.92***
                2     479.14          .00         .00         .00
  3     3             480.65     2609.92***
                1     480.49       140.00         .00      140.00
  3     4             481.35     2469.92***
                1     481.35          .00         .00         .00
  3     5             483.48     2469.92***
                1     483.90          .00         .00         .00
  3     6             484.77     2469.92***
                1     484.80          .00         .00         .00
```

```
LINE NODE   AREA        ELEV.        FLOW          OVERFLOW  AREA FLOW
                         FT.          GPM           GPM       GPM

  3    7               485.80      2469.92***
              1        486.08         .00            .00          .00
  3    8               489.03      2469.92***
              1        490.11         .00            .00          .00
  3    9               492.17      2469.92***
              1        493.17       291.80           .00       291.80
  3   10               492.38      2178.12***
              2        493.20        16.37           .00        16.37
  3   11               505.60      2161.75***
              2        506.60       173.70           .00       173.70
  3   12               512.86      1988.05***
              1        514.56       161.40           .00       161.40
  3   13               517.12      1826.65***
              2        518.12       145.05           .00       145.05
  3   14               527.75      1681.60***
              2        528.75       121.00           .00       121.00
  3   15               550.00      1560.60***
              1        551.50      1560.60           .00      1560.60
THE INFILTRATION RATE IS PRESENTLY .000 GALLONS/MIN/FT OF LATERAL
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RUN # 3

```
LINE  NODE  AREA   ELEV.       FLOW        OVERFLOW    AREA FLOW
                    FT.         GPM          GPM          GPM
  1     1         819.00    8217.89***
  1     2         822.94    8217.89***
  1     3         824.30    8217.89***
  1     4         825.01    8217.89***
  1     5         826.60    8217.89***
  1     6         828.03    8217.89***
              2   829.00      50.70           .00         50.70
  1     7         829.33    8167.19***
              2   830.83      91.00           .00         91.00
  1     8         834.78    8076.19***
              1   835.90      67.95           .00         67.95
  1     9         835.69    8008.24***
              1   836.50      88.80           .00         88.80
  1    10         838.36    7919.44***
              2   839.19     112.95           .00        112.95
  1    11         839.95    7806.49***
              1   840.40      29.58           .00         29.58
              2   840.60     173.90           .00        173.90
  1    12         840.61    7603.01***
              2   841.00     103.02           .00        103.02
  1    13         842.53    7499.99***
              2   842.61     162.55           .00        162.55
  1    14         846.59    7337.44***
              1   847.25     266.55           .00        266.55
              2   847.89      83.69           .00         83.69
  1    15         853.88    6987.20***
              1   853.83       2.25           .00          2.25
  1    16         856.36    6984.95***
              2   856.36      14.00           .00         14.00
  1    17         857.69    6970.95***
              2   857.70      20.25           .00         20.25
  1    18         860.12    6950.70***
              1   860.21     114.65           .00        114.65
              2   860.19     287.00           .00        287.00
  1    19         866.91    6549.05***
              1   867.10      18.15           .00         18.15
  1    20         869.88    6530.90***
              2   870.02     927.58           .00        927.58
  1    21         875.61    5603.32***
              1   875.68      74.90           .00         74.90
              2   876.10     458.25           .00        458.25
  1    22         878.49    5070.17***
              1   878.68      89.75           .00         89.75
  1    23         880.78    4980.42***
  2     1         880.78    2004.15***
  2     2         883.59    2004.15***
              2   883.63      63.42           .00         63.42
  2     3         896.58    1940.72***
              2   897.58     103.00           .00        103.00
```

```
                              ELEV.       FLOW          OVERFLOW    AREA FLOW
LINE    NODE    AREA          FT.         (CFS)         (CFS)       (CFS)
 2       4                    506.36     1837.70***
                 1            507.36         .00            .00           .00
 2       5                    516.84     1857.70***
                 1            517.84      302.65            .00        302.65
                 2            517.84       62.55            .00         62.55
 2       6                    538.00     1392.70***
                 1            539.00       57.85            .00         57.85
 2       7                    570.74     1334.87***
                 2            571.74       23.05            .00         23.05
 2       8                    573.11     1311.62***
 2       9                    575.62     1311.62***
                 2            575.70       62.80            .00         62.80
 2      10                    578.09     1248.82***
                 2            578.13       49.60            .00         49.60
 2      11                    579.52     1199.22***
                 2            579.62       49.60            .00         49.60
 2      12                    580.41     1149.62***
                 2            580.47       45.75            .00         45.75
 2      13                    582.38     1103.87***
                 2            582.47       46.50            .00         46.50
 2      14                    584.21     1057.37***
                 2            584.30       46.50            .00         46.50
 2      15                    585.75     1010.87***
                 2            586.03       27.50            .00         27.50
 2      16                    587.85      983.37***
                 2            588.00       60.25            .00         60.25
 2      17                    590.72      923.12***
                 1            590.72      *33.75          33.75           .00
                 2            590.84       58.75            .00         58.75
 2      18                    595.65      777.87***
                 2            595.65       11.62          50.37         62.00
 2      19                    597.74      882.25***
                 1            597.74      *33.75          33.75           .00
                 2            597.74        3.97          59.58         63.55
 2      20                    600.97      916.13***
                 1            603.00       16.27         244.03        260.30
                 2            600.37       10.36         155.39        165.75
 2      21                    610.71      889.50***
                 1            611.40      889.50            .00        889.50
 3       1                    880.70     2975.25***
 3       2                    881.77     2976.27***
                 2            881.77       *1.25           1.25           .00
 3       3                    884.65     2977.52***
                 1            884.95      155.75            .00        155.75
 3       4                    885.53     2821.77***
                 1            885.53         .00            .00           .00
 3       5                    886.21     2821.77***
                 1            888.21       *1.25           1.25           .00
 3       6                    887.69     2823.02***
                 1            889.69       *1.25           1.25           .00
```

```
LINE   NODE   AREA   ELEV.        HEAD        OVERFLOW  LEFT FLOW
                     FT.          FT          GPM       GPM
 3      7            491.11      0824.07***
               1     491.11        -1.05        1.05         .00
 3      8            495.37      0825.50***
               1     495.37        -1.05        1.05         .00
 3      9            475.46      0402.73***
               1     488.97       335.60         .00      335.60
 3     10            499.71      0491.17***
               2     499.75        19.87         .00       19.87
 3     11            508.01      0472.70***
               2     508.22       197.60         .00      197.60
 3     12            513.86      0275.10***
               1     514.86       194.15         .00      194.15
 3     13            517.19      0096.95***
               2     518.19       163.36         .00      163.36
 3     14            527.75      1927.65***
               2     528.75       135.85         .00      135.85
 3     15            550.00      1791.80***
               1     551.94      1791.80         .00     1791.80
  THE INFILTRATION RATE IS PRESENTLY  .01  GALLONS/MIN/FT OF LATERAL
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RUN # 4

```
LINE  NODE  AREA  ELEV.        FLOW         OVERFLOW    AREA FLOW
 1     1          419.00     8082.57***
 1     2          420.28     8082.57***
 1     3          424.18     8082.57***
 1     4          425.00     8082.57***
 1     5          426.60     8082.57***
 1     6          427.99     8082.57***
             2    429.20       62.65          .00         62.65
 1     7          429.49     8020.12***
             2    430.49      110.65          .00        110.65
 1     8          434.90     7889.47***
             1    435.90      100.55          .00        100.55
 1     9          435.58     7788.92***
             1    436.50      109.65          .00        109.65
 1    10          438.18     7680.27***
             2    439.01      149.95          .00        149.95
 1    11          439.67     7510.32***
             1    440.60       17.66        17.66         35.32
             2    440.30      202.90          .00        202.90
 1    12          440.29     7289.76***
             2    441.30      130.02          .00        130.02
 1    13          441.20     7159.74***
             2    442.31      201.55          .00        201.55
 1    14          446.82     6958.19***
             1    447.82       63.03       273.14        336.17
             2    448.35      109.31          .00        109.31
 1    15          453.60     6785.20***
             1    452.53        3.25          .00          3.25
 1    16          455.87     6782.59***
             2    455.88       20.50          .00         20.50
 1    17          457.13     6762.09***
             2    457.16       30.25          .00         30.25
 1    18          457.44     6731.14***
             1    460.06      149.95          .00        149.71
             2    459.55      378.82          .00        378.82
 1    19          466.10     6203.07***
             1    467.10       23.65          .00         23.61
 1    20          468.99     6179.42***
             2    469.28      616.07       616.07       1232.14
 1    21          474.15     5563.35***
             1    473.67       77.40          .00         77.40
             2    474.79      301.47       301.47        602.94
 1    22          477.51     5184.46***
             1    477.61       53.06        53.06        114.12
 1    23          479.90     5103.39***
 2     1          479.90     2031.27***
 2     2          481.21     2031.27***
             2    483.08       83.72          .00         83.72
 2     3          496.50     2147.56***
             2    497.58      133.87          .00        133.87
 2     4          506.36     2013.67***
             1    507.36       -3.75         3.75           .00
```

LINK	NODE	AREA	ELEV. FT.	FLOW CFM	OVERFLOW CFM	[illegible] FLOW CFS
2	5		516.98	2017.40***		
		1	517.24	251.91	251.91	503.82
		2	517.28	71.17	.00	71.17
2	6		532.00	1604.03***		
		1	539.00	73.05	.00	73.05
2	7		570.98	1610.03***		
		2	571.78	30.75	.00	30.75
2	8		572.51	1572.73***		
2	9		577.30	1574.73***		
		2	577.8[illegible]	57.40	.00	57.40
2	10		578.70	1600.03***		
		2	580.89	65.60	.00	65.60
2	11		582.67	1456.75***		
		2	582.[illegible]	65.20	.00	65.60
2	12		583.25	1371.13***		
		2	584.00	60.91	.00	60.35
2	13		586.51	1320.10***		
		2	586.60	61.50	.00	61.50
2	14		587.97	1268.60***		
		2	589.11	61.50	.00	61.50
2	15		591.25	1207.15***		
		2	591.40	61.50	.00	61.50
2	16		593.75	1185.51***		
		2	593.99	33.97	33.37	33.35
2	17		597.81	1115.71***		
		1	597.81	-33.75	33.75	.00
		2	597.81	16.61	60.09	77.90
2	18		605.13	1108.81***		
		2	605.18	15.37	65.62	80.00
2	19		608.28	1109.87***		
		1	608.18	-33.75	33.75	.00
		2	608.18	15.76	68.30	84.05
2	20		615.81	1107.87***		
		1	615.82	21.80	315.28	336.30
		2	615.85	39.05	184.20	209.25
2	21		626.59	1057.30***		
		1	627.66	1057.40	.00	1057.40
3	1		679.90	2872.10***		
3	2		681.77	2872.10***		
		2	681.76	-11.25	11.25	.00
3	3		682.55	2883.37***		
		1	683.67	97.56	97.56	195.12
3	4		686.81	2785.30***		
		1	686.81	-3.75	3.75	.00
3	5		687.03	2789.55***		
		1	687.03	-11.25	11.25	.00
3	6		688.51	2800.80***		
		1	688.50	-11.25	11.25	.00

```
LINE   NODE   AREA ELEV.        FLOW        AVEFLOW  AREA FLOW
                   FT.          GPM          GPM       GPM

  3      7          489.91      2812.05***
                1   489.90       -11.25       11.25        .00
  3      8          494.17      2823.30***
                1   494.16       -11.25       11.25        .00
  3      9          497.27      2834.55***
                1   497.51       222.55      222.55     265.10
  3     10          497.53      2612.00***
                2   497.55        11.86       11.86      23.72
  3     11          507.95      2600.14***
                2   507.95        48.25      209.10     257.35
  3     12          513.86      2551.89***
                1   514.86        45.17      175.57     241.02
  3     13          517.45      2506.70***
                2   518.12       164.46      164.46     208.92
  3     14          527.75      2462.23***
                2   528.75        32.43      140.54     172.97
  3     15          550.00      2369.80***
                1   550.24      2369.80         .00    2369.80
THE INFILTRATION RATE IS PRESENTLY .015 GALLONS/MIN/FT OF LATERAL
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```
                                  RUN # 5
LINE   NODE   AREA     ELEV.        FLOW          OVERFLOW     AREA FLOW
                        FT.          GPM            GPM          GPM
  1      1            419.00     9432.35***
  1      2            421.47     9432.35***
  1      3            425.72     9432.35***
  1      4            426.57     9432.35***
  1      5            428.00     9432.35***
  1      6            429.30     9432.35***
                2     429.47       62.45            .00          62.45
  1      7            432.45     9369.90***
                2     432.89      110.65            .00         110.65
  1      8            437.12     9259.25***
                1     437.12      100.55            .00         100.55
  1      9            438.00     9158.70***
                1     438.66      128.65            .00         128.65
  1     10            441.37     9030.05***
                2     442.77      140.95            .00         140.95
  1     11            443.77     8889.10***
                1     443.40       35.33            .00          35.33
                2     444.21      202.90            .00         202.90
  1     12            444.18     8650.87***
                2     445.21      139.02            .00         139.02
  1     13            445.31     8511.85***
                2     446.92      221.55            .00         221.55
  1     14            449.00     8290.30***
                1     450.11      159.55         176.62         336.17
                2     450.66      109.31            .00         109.31
  1     15            458.20     8021.44***
                1     458.20        3.25            .00           3.25
  1     16            461.30     8018.19***
                2     461.39       20.50            .00          20.50
  1     17            462.67     7997.69***
                2     463.10       30.25            .00          30.25
  1     18            463.16     7967.44***
                1     466.90      149.95            .00         149.95
                2     466.27      378.82            .00         378.82
  1     19            474.00     7438.67***
                1     474.65       23.65            .00          23.65
  1     20            478.45     7415.02***
                2     479.69     1232.14            .00        1232.14
  1     21            485.27     6182.88***
                1     485.39       99.42            .00          99.42
                2     486.08      600.95            .00         600.95
  1     22            488.50     5482.51***
                1     488.91      118.10            .00         118.10
  1     23            491.18     5382.37***
  2      1            491.18     2061.25***
  2      2            494.11     2061.25***
                2     494.18       83.70            .00          83.70
  2      3            500.96     1977.55***
                2     501.08      133.87            .00         133.87
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LINE   NODE   AREA  ELEV.         FLOW          OVERFLOW       FREE FLOW
                    FT.           GPM            GPM            GPM
  2      4          506.78      1843.65***
                1    507.36        -.35            .35             .00
  2      5          516.84      1844.00***
                1    517.84      503.82            .00          503.82
                2    517.84       81.17            .00           81.17
  2      6          538.00      1259.00***
                1    539.00       73.85            .00           73.85
  2      7          570.96      1185.15***
                2    571.96       30.75            .00           30.75
  2      8          571.91      1154.40***
  2      9          574.77      1154.40***
                2    574.90       57.60            .00           57.60
  2     10          576.68      1097.00***
                2    576.84       65.60            .00           65.60
  2     11          577.75      1031.40***
                2    577.92       65.60            .00           65.60
  2     12          578.40       965.80***
                2    578.55       60.95            .00           60.95
  2     13          579.76       904.85***
                2    579.91       61.50            .00           61.50
  2     14          580.76       843.35***
                2    581.11       61.50            .00           61.50
  2     15          582.04       781.85***
                2    582.19       61.50            .00           61.50
  2     16          583.16       720.35***
                2    583.40       79.95            .00           79.95
  2     17          584.70       640.40***
                1    584.70     -256.29         256.29             .00
                2    584.78       77.90            .00           77.90
  2     18          588.82       818.79***
                2    588.82        4.32          77.63           82.00
  2     19          590.64       814.47***
                1    590.63     -256.29         256.29             .00
                2    590.64        1.48          82.57           84.05
  2     20          597.60      1069.24***
                1    597.60         .66         335.64          336.30
                2    597.60        1.22         207.83          209.05
  2     21          603.39      1067.40***
                1    609.45     1067.40            .00         1067.40
  3      1          491.15      3321.12***
  3      2          493.62      3321.12***
                2    493.61       -9.49           9.49             .00
  3      3          495.96      3330.61***
                1    496.38      195.12            .00          195.12
  3      4          496.74      3135.49***
                1    496.94        -.35            .35             .00
  3      5          500.16      3135.84***
                1    500.16       -9.49           9.49             .00
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LINE   NODE   AREA  ELEV.        FLOW        OVERFLOW   ADDL FLOW
                    FT.          GPM         GPM          GPM
 3      6           501.84     3185.33***
               1    501.84       -9.49        9.49 '        .00
 3      7           503.58     3154.82***
               1    503.54      -28.48       28.48          .00
 3      8           508.87     3103.30***
               1    508.82      -28.48       28.48          .00
 3      9           512.67     2811.78***
               1    513.53      665.10         .00       665.10
 3     10           512.96     2766.68***
               2    513.03       23.72         .00        23.72
 3     11           524.45     2742.95***
               2    524.45       40.71      216.64       257.35
 3     12           529.78     2702.24***
               1    529.97      114.39      126.63       241.02
 3     13           533.56     2587.85***
               2    524.00      208.92         .00       208.92
 3     14           539.61     2378.92***
               2    539.61        7.12      163.85       170.97
 3     15           550.60     2369.80***
               1    553.26     2369.80         .00      2369.80
THE INFILTRATION RATE IS PRESENTLY .015 GALLONS/MIN/FT OF LATERAL
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METRIC CONVERSION TABLE

TO CONVERT...	INTO...	MULTIPLY BY...
acres	sq meters	4,047.
cubic feet	cu meters	0.02832
feet	meters	0.3048
feet of water	kgs/sq meter	304.8
feet/sec	cms/sec	30.48
feet/sec	meters/min	18.29
gallons	cu meters	3.785×10^{-3}
gallons	liters	3.785
gallons/min	liters/sec	0.06308
inches	centimeters	2.540
inches	meters	2.540×10^{-2}
Poise	Gram/cm.sec.	1.00
pounds	kilograms	0.4536
pounds/cu ft	kgs/cu meter	16.02
pounds/sq ft	kgs/sq meter	4.882
pounds/sq in	atmospheres	0.06804
Slug	Kilogram	14.59
temperature (°F) -32	temperature (°C)	5/9